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EXPERIMENTAL ASSESSMENT OF IMPROVED SPATIAL RESOLUTION LANDSAT --ETC(U)

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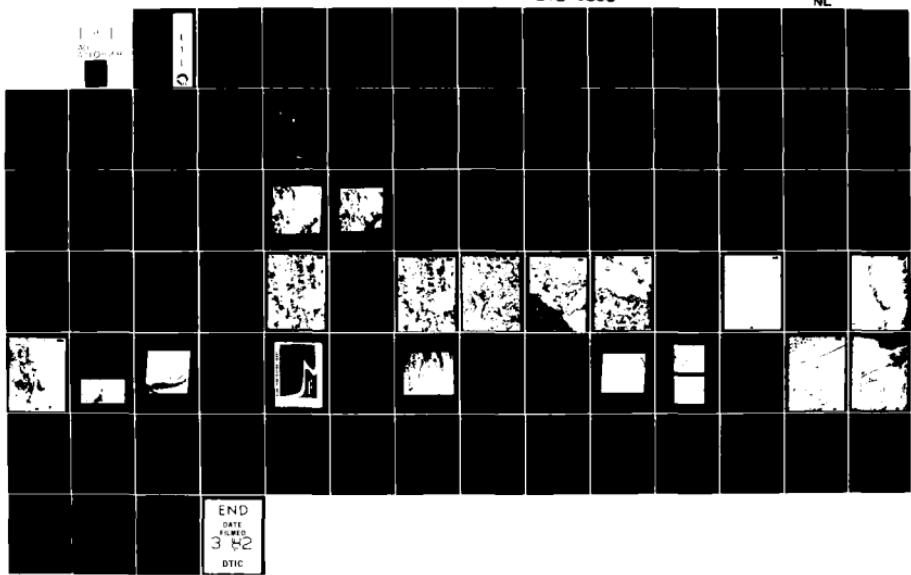
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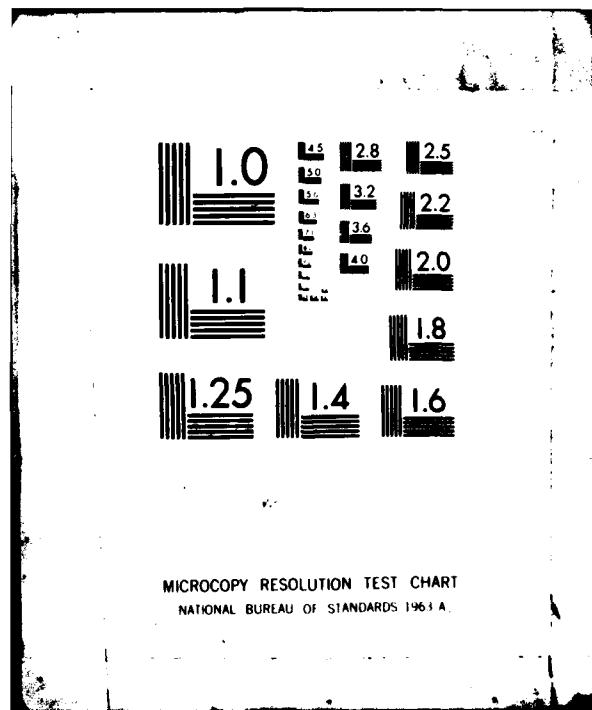
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Experimental assessment of
improved spatial resolution
Landsat data

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes the possible uses of higher resolution (25 meter) space-derived images for delineating and measuring surface features of interest in the Corps of Engineers' Civil Works Program. Following a discussion of imaging sensors and computer processing methods, test evaluations are described in which Landsat multispectral scanner data and SEASAT SAR data were interpreted for surface features. The comparative advantages of the two data sources are discussed, and the complementary nature of Landsat MSS and SEASAT SAR images		

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is displayed in the image analyses. Image examples are included for both background discussion and test site evaluation.

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PREFACE

This report was prepared under contract DAAK70-80-C-0016 for the U. S. Army Corps of Engineers, Engineer Topographic Laboratories, Fort Belvoir, Virginia.

We would like to acknowledge the assistance and contribution to this project of the Contracting Officer's Technical Representatives, Mr. Lawrence P. Murphy and Mr. Laslo Greczy, in obtaining and making available to us image tapes and collateral test area data for project performance.

EXECUTIVE SUMMARY

This report describes the analysis of Landsat and SEASAT data of the Elizabeth City and Duck coastal areas of North Carolina, with an evaluation of its potential use in Corps of Engineers' civil works programs. The main application areas are in shore-line mapping, lake and stream delineation, swamp and marsh delineation, urban area delineation, and the mapping of roads, bridges, and agricultural field patterns.

The report is structured as follows:

Section I describes the background for the study, with reference to the upcoming launch of Landsat-D. Following a description of relevant spacecraft and sensors in Section I, Section III describes the correction and enhancement processes applied on this project to image data in magnetic tape format. Section IV reviews the spaceborne data types available for project evaluation, and Section V lists these and the associated airborne and ground truth data bases. In Section VI the main interpretation results using Landsat and SEASAT data are described, comparing both data sources and their limitations. The conclusions to be drawn from this work are given in Section VII and recommendations for future simulations are in Section VIII.

A brief description of the processing system used on the project is contained in Appendix 1.

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EXPERIMENTAL ASSESSMENT OF IMPROVED SPATIAL RESOLUTION LANDSAT DATA

I. BACKGROUND - REASON FOR THE STUDY

Evaluation of Landsat data, and its potential application to a variety of land-based and coastal problems, began with the launch of ERTS-1 (now Landsat-1) in 1972. Over the past nine years investigators have become quite familiar with the uses and limitations of the Multi-spectral Scanner, which is the primary Landsat data source, and familiar to a lesser degree with the properties of Return Beam Vidicon data. Digital processing of magnetic tape data from Landsat has progressed a great deal in the same period, and enhancement and classification techniques continue to broaden the possible uses of the data received from Landsat-1, -2, and -3.

In 1982, the launch of Landsat-D will signal the arrival of the next generation of earth resources satellites. This new generation will be characterized by a number of improvements: spectral range will be extended, spectral resolution will be improved, spatial resolution will sharpen, more intensity levels will be measured, more frequent ground coverage will be possible, and stereo images will become available. All these capabilities do not reside in a single satellite. The characteristics of Landsat-D, SPOT, ERS, and the proposed instruments of Mapsat, Stereosat and Shuttle Imaging Radar (SIR) are briefly described in the next section.

In order to gain a better understanding of the way in which the new instruments will prove useful to Corps of Engineers' programs, the U.S. Army Engineer Topographic Laboratories in 1980 initiated a study project to evaluate certain elements of the new generation of satellites' performance, utilizing for this purpose combinations of available satellite imagery, supported for evaluation purposes by ground truth and aerial instrument coverage.

The results of this study are reported here. Following a summary discussion of spacecraft systems and sensors, computer processing methods to handle digital data tapes are described as they have been employed on this project. This is followed by a review and critique of the available data sources. Specific interpretations are provided for two North Carolina test sites, employing Landsat digital data, SEASAT digital data, and a complete supporting aerial data base and ground truth survey. Emphasis in the interpretation was placed upon certain key areas of Corps of Engineers civil works, as follows:

- Shoreline and Inlet Mapping & Studies
- Dredging Deposit Detection
- Lake and Stream Delineation
- Swamp and Marsh Delineation
- Urban Area Delineation and Studies
- Roads, Related Patterns and Bridges
- Agricultural Field Line Patterns

Following these results, this report provides an overall evaluation, with suggestions for possible additional work by the Corps of Engineers using Landsat-D simulated data.

Project Chronology

As originally conceived, it was intended that this study would make use of the Landsat-3 Return Beam Vidicon data,* which, with its 30 meter resolution, should approximate the degree of detail visible on a Landsat-D

*See Section II for the description of this and other relevant sensors and spacecraft.

image, although without of course possessing the corresponding spectral range.

In the first months of the project, considerable effort was made to obtain Landsat-3 digital RBV tapes, which could be manipulated on the computer to yield enhanced products. When tapes of suitable test areas were finally obtained, their quality was a great disappointment. The apparent resolution of the images, even after enhancement, looks far inferior to 30 meters (examples are shown in Section IV). It was therefore decided to modify the approach to the study, and to employ SEASAT Synthetic Aperture Radar (SAR) as the higher resolution data source in place of Landsat-3 RBV. This introduces some complication in analysis because, whereas Landsat multispectral scanner and RBV data have approximately the same geometry (particularly if the images have been acquired at the same time), by contrast, SEASAT SAR data and Landsat MSS data are considerably distorted geometrically with respect to each other. The problems this introduces, and the approach used to overcome them, are described in Section VI.

II. PLATFORMS AND SENSORS

The emphasis in this section is on properties of the Landsat-D space-craft, and properties of the Landsat-1, -2 and -3 and SEASAT systems that were used in the analysis for the project. For completeness, brief summaries are also provided here of several other systems, past and future, which because of their resolution or spectral range provide relevant information on the possible appearance and use of Landsat-D data.

A. Landsat-1, -2, and -3 Spacecraft

1. Orbit

Three Landsat spacecraft have so far been launched by NASA. Each of them moves in a sunsynchronous orbit with 103 minute period, inclination 99°, eccentricity close to zero, and mean semi-major axis 7,290 kilometers. The mean altitude of the spacecraft is thus about 910 kilometers.

Observations of the earth are made on the daylight side (see note below on Landsat-3 thermal channel), which is traversed on the descending node of the orbit with mean local equatorial crossing time of 9:30 a.m. Each satellite provides imagery for complete coverage of the earth's surface in latitudes lower than 81° every 18 days. Landsat-1 was launched in July 1972, Landsat-2 in January 1975, and Landsat-3 in March 1978. Landsat-1 is no longer functioning.

2. Multispectral Scanner

The primary observing instrument on Landsat-1, -2, and -3 has been a Multispectral Scanner (MSS), with instantaneous field

of view of approximately 79 meters by 79 meters on the surface of the earth. Observations are made in four spectral ranges:

- 0.5 - 0.6 micrometers (visible yellow);
- 0.6 - 0.7 micrometers (visible red);
- 0.7 - 0.8 micrometers (infrared Band 1); and
- 0.8 - 1.1 micrometers (infrared Band 2).

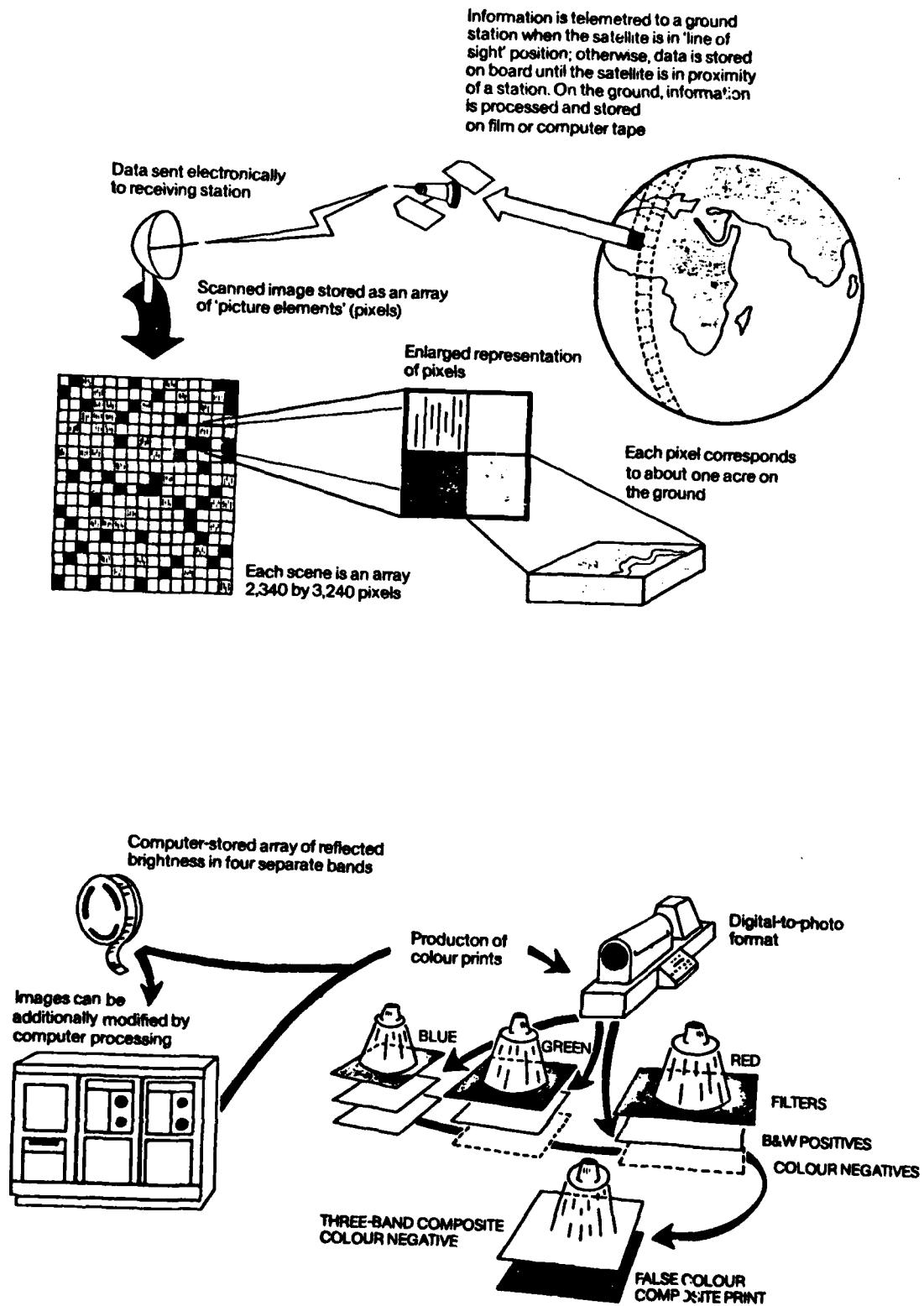
These four bands are conventionally termed Bands 4, 5, 6, and 7 for reasons described below. Oversampling the analog electrical signal from the MSS produces in the digital telemetry picture elements that are each approximately 57 meters by 79 meters.

The swath width on the ground covered by the scanner is 185 kilometers wide, and for convenience of processing the swath is divided in the satellite along-track direction into 185 kilometer portions, with each resulting 185 by 185 kilometer picture element array being termed one scene or frame.

The observed ground reflectances are quantized to 64 reflectance levels in each spectral band. Although ground processing of the images later assigns reflectances to a range of 256 grey levels, it should be noted that the number of discernibly different grey tones in an image is no more than 64. The overall information flow for MSS imagery is shown in Figure 1. Data from the MSS sensors is available in both image (film and print) and Computer Compatible Tape forms.

Note concerning the Landsat-3 Thermal Channel: Landsat-3 carried a fifth channel in thermal infrared, with a spectral range

FIGURE 1 - General Information Flow for Processing of Landsat MSS Images



from 10.4 to 12.6 micrometers, and an instantaneous field of view of 240 meters by 240 meters. This instrument was intended to provide thermal imagery on either day side or night side passes. However, one of the two detectors for this sensor failed immediately upon launch, and no data from the instrument was ever released by NASA for general evaluation.

3. Return Beam Vidicon

Ninety-eight percent of the data processed from the Landsat spacecraft to date has been multispectral scanner (MSS) data. However, in addition to the scanner, the first two Landsat spacecraft also carried a second imaging system, a 3-camera Return Beam Vidicon (RBV) with spectral ranges 0.475 to 0.57, 0.58 to 0.68, and 0.7 to 0.83 micrometers. Problems with the spacecraft unrelated to actual RBV performance meant that little RBV data was obtained on either Landsat-1 or Landsat-2. Images from the RBV were intended to constitute Bands 1, 2 and 3 of Landsat data, hence the number assignment of the MSS bands.

Landsat-3 carries a different form of RBV consisting of two panchromatic cameras (spectral range 0.505 to 0.750 micrometers) mounted side by side in the spacecraft and each imaging a square of 98 Km². They have an image overlap of 14 Km, and four Landsat-3 RBV images cover roughly the same area as a single MSS scene. However, the discernible ground field of view of the RBV is significantly better than that of the MSS, and for a medium contrast scene, resolution is about 30 meters.

Like the MSS data, the RBV data from Landsat-3 is also available in either film or Computer Compatible Tape form. However, considerable difficulties were experienced during this project in obtaining good quality digital tapes of RBV data. Image samples are presented in Section IV of this report.

B. Landsat-D

1. Orbit

Landsat-D is planned for a launch in the Fall of 1982. It, and its identical successor Landsat-D', will be in sun-synchronous orbits, rather lower in height than Landsat-1, -2, and -3, with a mean height of 705 Km. Like earlier Landsat's the inclination of the orbit will be about 99°. Landsat-D will have a repeat ground coverage of 16 days rather than the 18 days of Landsat-1, -2, and -3. Selection of the lower orbit was initially justified to permit Space Shuttle retrieval. However, this will not be possible until Vandenberg Shuttle launches begin about 1986. Like the earlier Landsat's, Landsat-D images the day side of the earth during the descending node of the orbit with mean equatorial crossing time of 9:30 a.m.

2. Multispectral Scanner

Landsat-D will carry a redesigned MSS, which will have identical spectral ranges and spatial resolution to the instruments flown on the first three Landsat spacecraft. This MSS will be the prime instrument in providing data continuity in the program.

3. Thematic Mapper

The Thematic Mapper will be the prime instrument in providing experimental products from Landsat-D. The assessment of the potential value of Thematic Mapper data is the prime objective of the present project.

The Landsat-D Thematic Mapper (TM) will observe in seven spectral ranges as follows:

0.45 - 0.52	micrometers	(visible blue-green)
0.52 - 0.60	"	(visible yellow)
0.63 - 0.69	"	(visible red)
0.76 - 0.90	"	(first infrared, sensitive to vegetation density)
1.55 - 1.75	"	(sensitive to leaf water content and separates clouds from snow)
2.08 - 2.35	"	(sensitive to altered [mineralized] rock); and
10.4 - 12.5	"	(thermal band)

Each of the first six of these has a ground resolution of 30 meters, and the seventh (thermal) band has a ground resolution of 120 meters. The Thematic Mapper will permit observation at 256 discrete quantization levels as compared with the 64 levels of Landsat-1, -2, and -3. The Thematic Mapper, like the MSS, is a scanning instrument, but unlike the MSS it performs two-direction scans. A hardware scanline corrector on the spacecraft permits data registration.

C. SEASAT1. Orbit

The SEASAT-1 spacecraft was launched in June 1978 and failed in October 1978 as a result of a major electrical short circuit; thus only three and a half months of collected data are available. The ~~spacecraft~~ moves in a nearly circular orbit, at a mean altitude of 800 km and an inclination of 108°.

Although primarily designed for the observation of oceanic phenomena, SEASAT recorded data over many land areas, particularly in the United States. The spacecraft carried five major sensors, only one of which, the Synthetic Aperture Radar (SAR), is of interest to the present project.

2. SEASAT Radar

The radar on the SEASAT spacecraft is a synthetic aperture instrument deriving its imaging capability through the forward motion of the spacecraft. The instrument operates at a frequency of 1.27 GHz (23.5 centimeter wavelength), and data processed at full resolution has a ground field of view of about 25 meters and a swath width of 100 Kms. Reconstruction of an image from the original radar signal is a substantial task, and interpretations made for this project (see Sections IV and VI) suggest to EarthSat interpretation staff that even the best resolution SEASAT data available for this project does not possess resolution as good as 25 meters.

Since radar is an active device, providing its own scene illumination, different parts of a SEASAT radar scene display different obliquities in illumination angle. This complicates the interpretation process, as does the fact that ground reflectances in the microwave region differ markedly from the familiar visible or near-infrared reflectances. Comparison of results obtained from the interpretation of SAR data with those obtained from Landsat is therefore a complex task. This question is discussed in more detail in Section VI.

SEASAT SAR images contain a distortion in the across-track direction owing to the varying range distance between space-craft nadir and the target point. For digitally processed images, picture element size varies because of this from 14.8 meters in the far across-track range to 19.4 meters in the near across-track range. Along-track picture element size is roughly constant at 16 meters. This variability of within-scene scale also adds some complexity to the interpretation problem, particularly in registering SEASAT with other data sources.

D. SPOT

As mentioned earlier, Landsat-D represents only the first of a series of new earth sensing satellites. One of the most significant of the new instruments is the French SPOT system (Système Probatoire d'Observation de la Terre), scheduled for 1984 launch. The SPOT satellite has a nominal altitude of 822 Km, a sunsynchronous orbit, and a repeating ground track period of 26 days. The two

observing instruments on board are Multiple Linear Arrays (MLA), with panchromatic (0.51 - 0.73 micrometers), 10 meter resolution, and with color (0.5 - 0.59, 0.61 - 0.69, and 0.79 - 0.90 micrometers) 20 meter resolution. The satellite will also have the capability to swing the mirrors of one or both of the observing instruments up to 26° sideways from the nadir, thereby permitting stereo imaging of any portion of the earth's surface (below 81° in latitude) utilizing successive days of coverage. In addition, sideways viewing permits coverage of a particular area of interest on an average of every 2-1/2 days.

SPOT lacks the extended spectral range of Landsat-D, but its very high resolution makes it a contender for a variety of applications that currently use airphoto coverage.

There appear to be no U.S. plans for a civilian Multiple Linear Array instrument that could be flown earlier than 1988.

E. Other Future Satellites

A number of other high resolution satellite systems have been proposed for flight in the next few years. They will be described here only in the briefest summary.

Mapsat is a 10 meter resolution stereo mapping satellite proposed by the U.S. Department of the Interior. It would have three spectral bands (0.47 - 0.57, 0.57 - 0.70, and 0.76 - 1.05 micrometers) and be designed as the name suggests primarily for map

making and particularly digital terrain modeling. The program is proposed but not approved.

Stereosat is a system proposed by the GEOSAT Committee for use in geological exploration. It would provide a 15 meter resolution panchromatic (0.5 - 0.9 micrometers) stereo capability. The project has been designed but does not have current funding.

The Large Format Camera to be flown on the Space Shuttle will provide capability similar to that of SPOT, namely, 10 meter resolution in black and white, and 20 meter ground resolution using color film. Currently the system is assigned to the OSTA-3 shuttle payload, tentatively designated to be flown in August 1984. Since this instrument will be carried on the Shuttle, images will be restricted to latitudes below 45°.

The Shuttle Imaging Radar (SIR) is a synthetic aperture, L-band radar with a proposed ground resolution of about 38 meters. Like the Large Format Camera, it will not be able to provide high latitude ground coverage.

F. Other Relevant Spaceborne Systems

Three other satellites and sensors should be mentioned briefly. These are systems which have already been flown and which, either spectrally or spatially, could offer information about the probable performance of Landsat-D.

The Coastal Zone Color Scanner is a 6 channel scanning instrument with narrow spectral windows (0.43 - 0.45, 0.51 - 0.53,

0.54 - 0.56, 0.66 - 0.68, 0.70 - 0.80, and 1.05 - 1.25 micrometers) extending from the blue to the shortwave infrared.

However, although spectrally the instrument provides analogs to Landsat-D wavelengths, its coarse resolution of 825 meters omits so much detail that direct comparisons with Thematic Mapper data are probably not meaningful.

Similarly, the Advanced Very High Resolution Radiometer (AVHRR), despite its name, has a ground resolution of 1 kilometer. Despite its interesting spectral properties (0.55 - 0.66, 0.725 - 1.10, 3.55 - 3.93, and 10.5 - 11.5 micrometers), it too is not a useful tool for Thematic Mapper comparisons when scene detail is important.

Finally, the S190A and S190B cameras carried on the Skylab missions in 1973 provided black and white, natural color, and color infrared images with roughly 30 meter resolution. Although the degree of detail visible on Skylab photography is excellent, its non-digital nature and non-systematic coverage of the earth makes it almost useless for assessments of the type conducted here. The S192 13-channel scanner carried by Skylab might seem to offer a more useful tool for digital comparisons. However, the S192 data with its conical scan pattern and high image noise make it too difficult to use in work of this type, even though its resolution is very close to that of the Landsat MSS (68 x 72 meter picture element).

The main characteristics of the sensors described in this section are summarized in Tables 1 and 2.

Table 1

II-11

Resolution and spectral distribution for resource satellites, 1972-1984

<u>Instrument</u>	<u>Ground Field of View</u>	<u>Spectral Distribution</u>	<u>Status</u>
Multi-Spectral Scanner ⁽¹⁾ (Landsat 1, 2, 3 and D)	79 meters (sampled to 57 x 79 meter pixel)	0.5 - 0.6 μ m 0.6 - 0.7 0.7 - 0.8 0.8 - 1.1	Flown
Return Beam Vidicon ⁽¹⁾ (Landsat 1 and 2)	65 meters (medium contrast scene; little data available from these instruments)	0.475 - 0.57 μ m 0.58 - 0.68 0.70 - 0.83	Flown
Return Beam Vidicon ⁽²⁾ (Landsat-3)	30 meters (medium contrast scene)	0.505 - 0.90 μ m	Flown
Thermal Infra-Red ⁽²⁾ Channel (Landsat-3)	240 meters (Note: data from this sensor was never re- leased)	10.4 - 12.6 μ m	Flown
SEASAT Synthetic ⁽³⁾ Aperture Radar	25 meters (data only from July to October, 1978)	1.27 GHz	Flown
Coastal Zone Color Scanner ⁽³⁾	825 meters	0.43 - 0.45 μ m 0.51 - 0.53 0.54 - 0.56 0.66 - 0.68 0.70 - 0.80 1.05 - 1.25	Flown
AVHRR (Advanced Very High Resolution Radio- meter on NOAA-6)	1000 meters	0.55 - 0.68 μ m 0.725 - 1.10 3.55 - 3.93 10.5 - 11.5	Flown
Thematic Mapper ⁽⁴⁾ (Landsat-D)	30 meters	0.45 - 0.52 0.52 - 0.60 0.63 - 0.69 0.76 - 0.90 1.55 - 1.75 2.08 - 2.35	For Fall 1982 Launch
	120 meters	10.4 - 12.5	
SPOT ⁽⁵⁾	20 meters	0.50 - 0.59 μ m 0.61 - 0.69 0.79 - 0.90	For 1984
	10 meters	0.50 - 0.75	Launch
Stereosat ^(6,7) (Proposed, but no approved program)	15 meters (tentative)	0.5 - 0.9 μ m (tentative)	Flight Date Unknown
Mapsat (Proposed, but no approved program)	10 meters	0.47 - 0.57 μ m 0.57 - 0.70 0.76 - 1.05	Flight Date Unknown
ERS (Japanese system, details not yet available)	Not specified	Visible, infrared, thermal infrared, and radar	Proposed 1986 Launch

Table 2
SKYLAB CHARACTERISTICS

S190A Film Characteristics

Wavelength (μm)	Film	Dynamic Resolution On the Ground (m)
0.5-0.6	PAN-X B&W (SO-022)	30
0.6-0.7	PAN-X B&W (SO-022)	28
0.7-0.8	IR B&W (EK 2424)	68
0.8-0.9	IR B&W (EK 2424)	68
0.5-0.88	IR Color (EK 2443)	57

S192 Scanner Characteristics

Channel	Spectral Bandwidths (μm)
1	.41 - .46
2	.46 - .51
3	.52 - .56
4	.56 - .61
5	.62 - .67
6	.68 - .76
7	.78 - .88
8	.98 - 1.09
9	1.09 - 1.19
10	1.20 - 1.30
11	1.55 - 1.75
12	2.10 - 2.35
13	10.20 - 12.50

III. COMPUTER PROCESSING

A. Properties of Data

The principal data sources used on this project are the Landsat Multispectral Scanner data, the Landsat-3 Return Beam Vidicon data, and the SEASAT-1 Synthetic Aperture Radar data. Although there are substantial differences between images obtained from these three instruments, there are many processing similarities. In particular, the following applies to all three images:

- (1) Received data from the satellite is via telemetry, thus all images are constructed from an initially digital (PCM) signal.
- (2) Images are synoptic, with a single image covering 10,000 square kilometers (RBV and SEASAT SAR) or 34,000 square kilometers (Landsat MSS).
- (3) The telemetered information, as recorded on magnetic tape, retains a greater dynamic range than can be expressed on any single piece of film. Opportunities for "tuned" products, emphasizing one class of information at the expense of others, therefore exist. Enhancement must be performed in computer processing prior to the creation of a photographic product, if tuned products are to be provided.
- (4) Images from all data sources depart from orthophoto geometry, though each in different ways. MSS data, because it is provided by a scanner and images different parts of a scene at different times, contains dis-

tortions due to earth rotation and mirror sweep effects; RBV data contains image tube distortion effects; and SAR data is distorted by range variations (SEASAT radar obliquities vary between 17 and 23 degrees away from the nadir at the near-range and far-range limits).

In addition, all data sources share common distortions caused by earth curvature, finite viewing distance and terrain variation. It is necessary to compensate for all of these effects in some way if comparative analysis is to be performed.

B. Image Correction and Enhancement

Although there is overlap between the two categories, it is productive to regard the processing of space-imaged data in two parts: correction and enhancement. Within these two categories it is also useful to distinguish two forms: radiometric processing and geometric processing. Each of the four possible subcategories will be discussed separately.

1. Radiometric Corrections

These corrections are important only in the case of Landsat MSS data where multiple detectors are used in sensing the ground scene. Each spectral band of MSS data is recorded using six separate detectors, mounted side by side so that a single sweep of the scan mirror provides six parallel traverses of the terrain. Since each detector has a slightly different response to incoming radiation, the uncorrected image made from

raw data will display a characteristic "striping" or "banding" with a spatial frequency of 474 meters (6 x 79).

Elimination of striping may be attempted in two different ways. One method is to calibrate the six on-board detectors of each spectral band against a standard on-board source of illumination. The other method matches to each other the frequency histogram of reflectance values obtained from each of the six detectors. Both methods are currently in use by different groups. In EarthSat's experience, the technique of matched histograms is superior to attempted on-board calibration, and the former method has been used in the work of this project.

During the radiometric correction process, the grey level range for Landsat MSS data is expanded from 64 to 256, to permit a finer relative adjustment of grey levels from the six detectors in each band. An example of a Band 7 Landsat MSS image before and after striping is shown in Figures 2A and 2B.

No analog of this problem exists for either RBV or SEASAT SAR data. Although not a radiometric distortion in the usual sense, SEASAT data has another peculiarity which affects image appearance. Whereas the visible and near-IR radiation seen by Landsat contains all polarizations, SEASAT was operated in a single polarization mode, namely that of a horizontally polarized signal and horizontally polarized sensed return.

FIGURE 2A



FIGURE 2B

FIG. 2 200-17275 07 OCT 76 KOT-22 1114-97 P002 RICH DILIGENT NEVER



Radar reflected signals are terrain dependent. In rough terrain, horizontal and vertical polarization measurements are almost equal. In smooth terrain, horizontal-polarization measurements from unpolarized incident radiation will be up to 15 db below vertical-polarization measurements.⁽⁸⁾ When the horizontally polarized signal from SEASAT SAR meets the ground, it is depolarized to varying degrees depending on the terrain. Part of the reflected signal will be vertically polarized. As a result, the energy of return signal to an instrument that senses only horizontally polarized radiation is reduced, and the reduction is terrain-dependent. These effects are observed, for example, when radar images are produced of crops and plant communities with pronounced vertical orientation. Photographic examples illustrating horizontal-horizontal and horizontal-vertical signal and sensed returns may be found in Reference 9 (Page 1,000).

2. Radiometric Enhancement

The histogram obtained from a typical spaceborne data source (see Figure 3 for an example) usually consists of a pronounced peak with rapidly diminishing tails. Often, substantial parts of the original grey level range are unpopulated or nearly so. If an image is produced directly from such a distribution it lacks contrast and is a poor tool for interpretation.

Computer processing can be used to modify the histogram before an image is created, so that it occupies all the available grey level range and thus improves the useful contrast of the result. This type of differential contrast adjustment is usually called a "stretch algorithm." Using digital processing, very general contrast adjustments are possible. Many different stretch algorithms have been developed. The most commonly used are probably the linear stretch, in which the given histogram is uniformly stretched to occupy the full grey level range; and the histogram equalizing stretch, in which the most populated grey levels are the most separated from their neighbors. These two stretches are shown in diagrammatic form in Figure 4.

A generalized version of these two types of contrast stretch, termed a hybrid stretch, has been developed by EarthSat and is our most commonly used technique for contrast adjustment. In a hybrid stretch, the population in each grey level value of the histogram is weighted by a power (P) of the occupancy number at that grey level. This permits linear stretches ($P=0$) and histogram

FIGURE 3 - SAMPLE HISTOGRAM BEFORE CONTRAST ADJUSTMENT

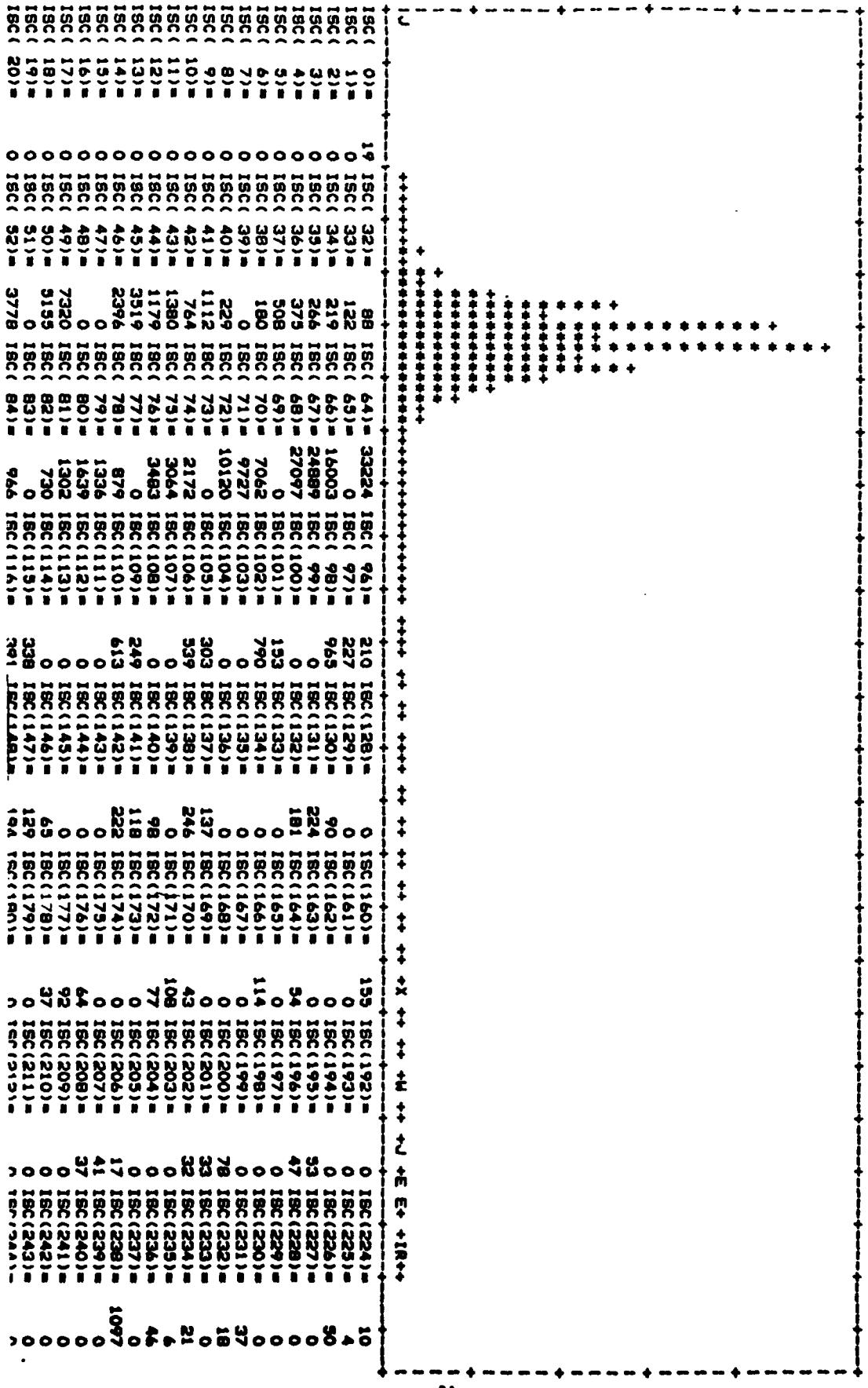


FIGURE 4A - Effect of the Linear Stretch

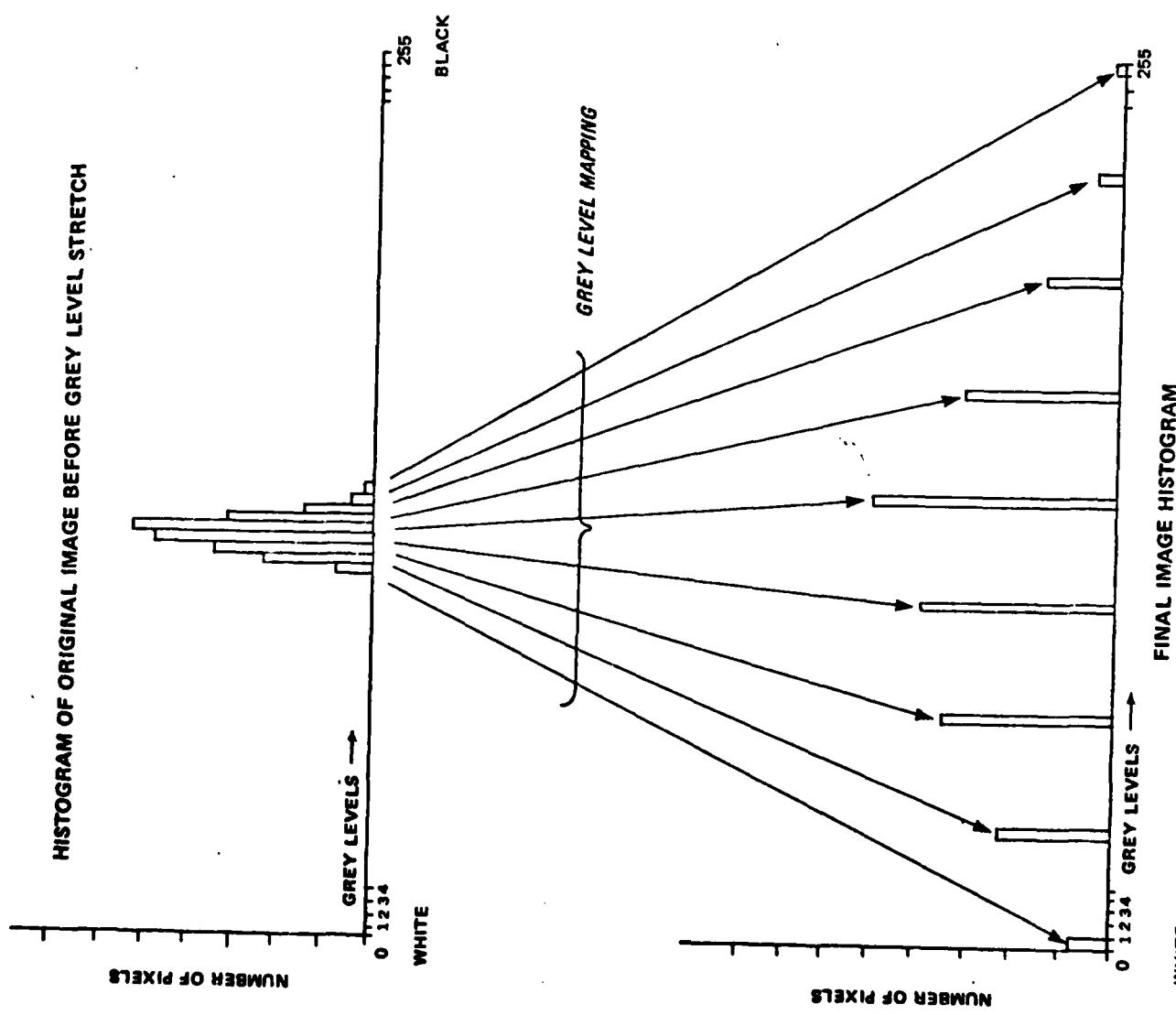
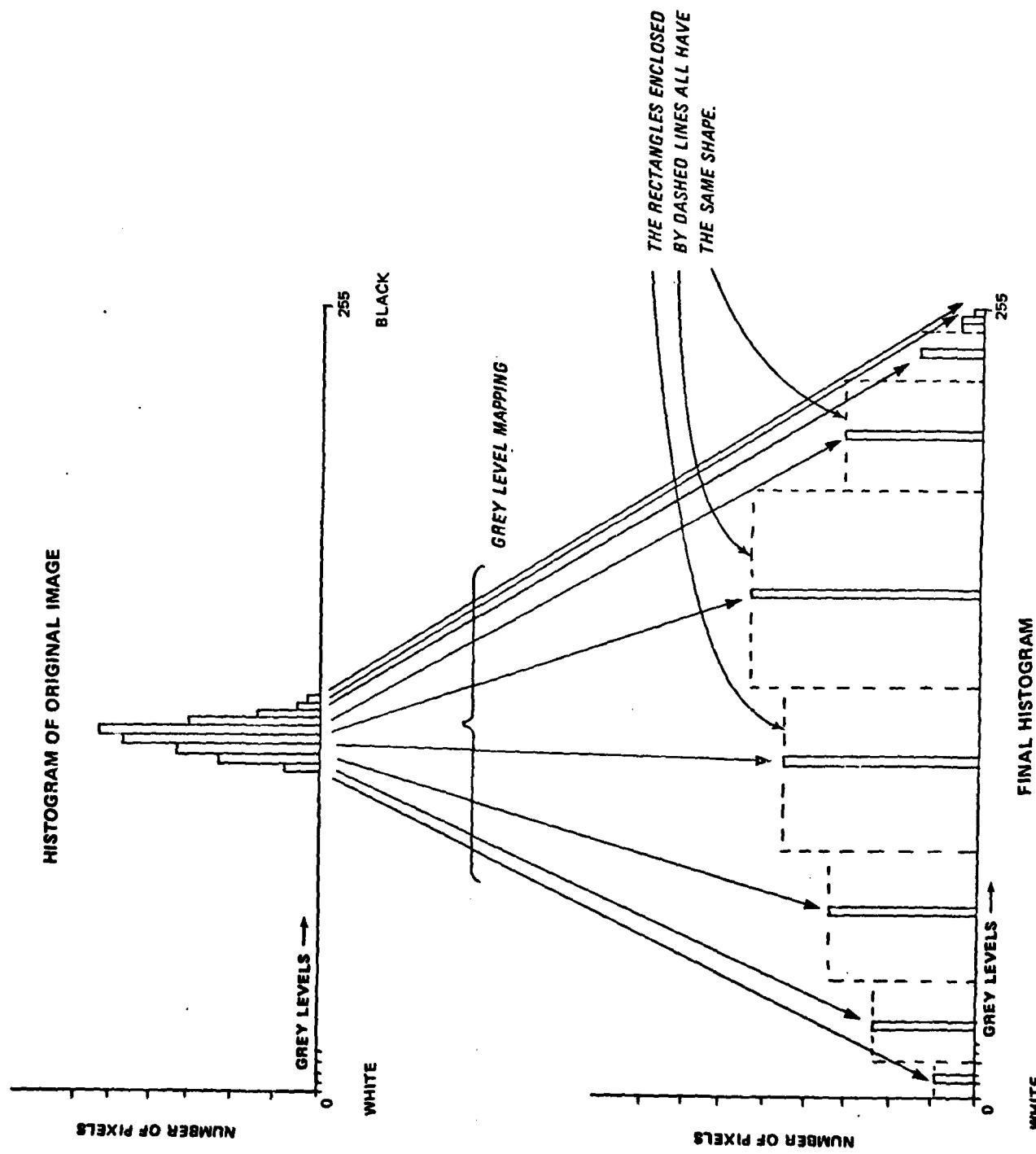


FIGURE 4B - Effect of the Histogram Equalizing Stretch



equalizing stretches ($P=1.0$), plus numerous intermediate stretch procedures ($0 < P < 1$). Contrast adjustment using hybrid stretches was performed on all the image data examples discussed in Sections IV and VI. The histogram of Figure 3 after a hybrid stretch with $P=0.7$ is shown in Figure 5.

3. Geometric Corrections

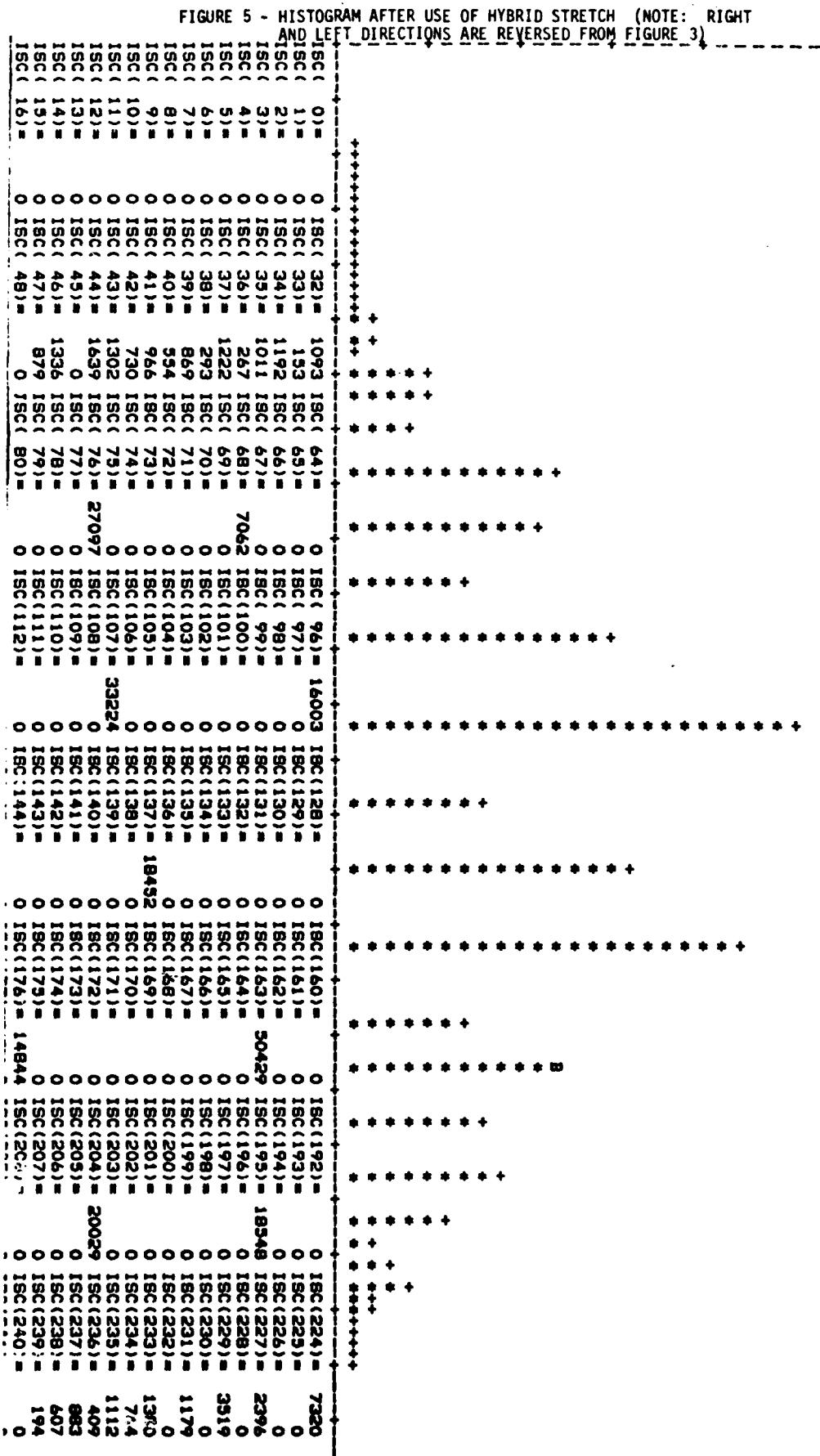
Principal geometric error sources in each data type

(a) Multispectral Scanner

- Earth rotation effect (Unlike a camera, a scanner takes a significant time to observe the area covered by one scene, and the earth's rotation during this time causes a skewing of the resulting image.)
- Earth curvature effects
- Finite altitude effects (Since the scanner has a look angle aperture of 5.76° , this introduces panoramic distortion which must be corrected.)
- Variations in scan mirror sweep velocity and scan mirror sweep angle produce variable scanline length and changes within scanlines.
- Satellite height and satellite attitude produce differential scale effects in the along-track and across-track directions, and also produce additional skewing.

EACH * = 2320

HISTOGRAM TABLE FOR SCANNED PICTURE AFTER GRAY SCALE PROCESSING



Following geometric correction, each MSS Landsat scene consists of a skewed array of picture elements each 57 meters x 79 meters, with roughly 3,240 picture elements along each scanline and 2,340 scanlines in a full image. Since each spectral band is generated by the decomposition of a single radiation input stream of ground reflectances, the four spectral bands that constitute a Landsat scene are registered with each other to an accuracy of a few meters.

NOTE: The above comments exclude discussion of the Landsat-3 thermal band, for which, as noted earlier, no data has ever been released.

(b) Landsat RBV data

Many of the sources of geometric distortion here are common to both MSS and RBV images. Each RBV camera records an area 99 Km x 99 Km; thus an individual RBV scene is less affected by certain distortions, notably earth curvature and panoramic effects. RBV data requires correction for:

- Changes in satellite height and satellite attitude.
- Finite altitude effects.
- Earth curvature effects.

- Linear and non-linear screen distortion.
- Scale variation produced by long period changes in image size on the vidicon tube.
- Read-out variations in converting the TV image to a telemetry data stream.

Following geometric correction and resampling, a digital RBV data tape contains an array of 5,322 x 5,322 picture elements. It will be noted that although the resolution (for medium contrast scenes) of the Landsat-3 RBV instruments is about 30 meters, the digital tape is sampled at a spacing of 18.6 meters (99 Km ÷ 5,322). This oversampling implies very high correlation between neighboring picture elements, and encourages the use of smoothing algorithms in the geometric enhancement process.

(c) SEASAT SAR data

This is the most complicated of the data sources considered here, and also the one least within the control of the study. The basic signal is not in image format. As with any synthetic aperture instrument, an image must be reconstituted from a large number of successive radar reflectance signals.⁽¹⁰⁾ This entire pre-processing is performed before a SEASAT digital tape is released to the user, and little information is provided with the tape

concerning the way in which geometric corrections are performed during the pre-processing phase.

However, it is certain that the following factors affect the geometric fidelity of the resulting SEASAT SAR image: (11,12)

- Earth curvature effects.
- Changes in satellite height and satellite attitude.
- Panoramic distortion.
- Terrain elevation (This is a much more significant variable for SEASAT SAR data than for Landsat data because of the oblique look angle, which may be as much as 23° away from the vertical.)
- Across-track scale changes.
- Variations in satellite velocity (which are critically important in the reconstitution of an image from the raw radar signals).
- Earth rotation effects (The radar image is constructed from radar return signals taken over a 20 second period.)

The geometrically corrected SEASAT SAR image (for which no range correction has been performed) consists of an array of 6,144 x 6,144 picture elements, covering a ground area of 100 Km x 100 Km.

4. Geometric Enhancement

The contrast adjustments described in Section III.B.2 are applied to the whole scene, and they do not employ any local spatial information about the scene in computing new grey level values for each picture element. In local edge enhancement and smoothing operations, on the other hand, the grey level adjustment at any picture element depends upon the grey level of spatially neighboring picture elements. Edge enhancement is used to increase the visibility of features of small spatial extent within an image, whereas smoothing is used to reduce the effects of electronic noise within an image.

Landsat MSS and RBV and SEASAT SAR data call for substantially different enhancement operators. Both MSS and RBV data are oversampled in creating digital tapes (the RBV to a greater extent than the MSS). Neighboring picture elements are therefore highly correlated in information content, and good opportunities exist for image sharpening, by the use of edge enhancement operators. In the case of RBV data, however, substantial electronic noise works to reduce the advantage of edge enhancement. EarthSat's experiments suggest that MSS data almost always benefits from edge enhancement, but that digital RBV data does not. SEASAT SAR, which like all radar imagery is highly monochromatic, has much electronic noise (which may in fact be statistical effects due to photon limitation) and displays the characteristic scintillation patterns of a radar image. In such a case, the high-pass filter of edge enhancement operators would

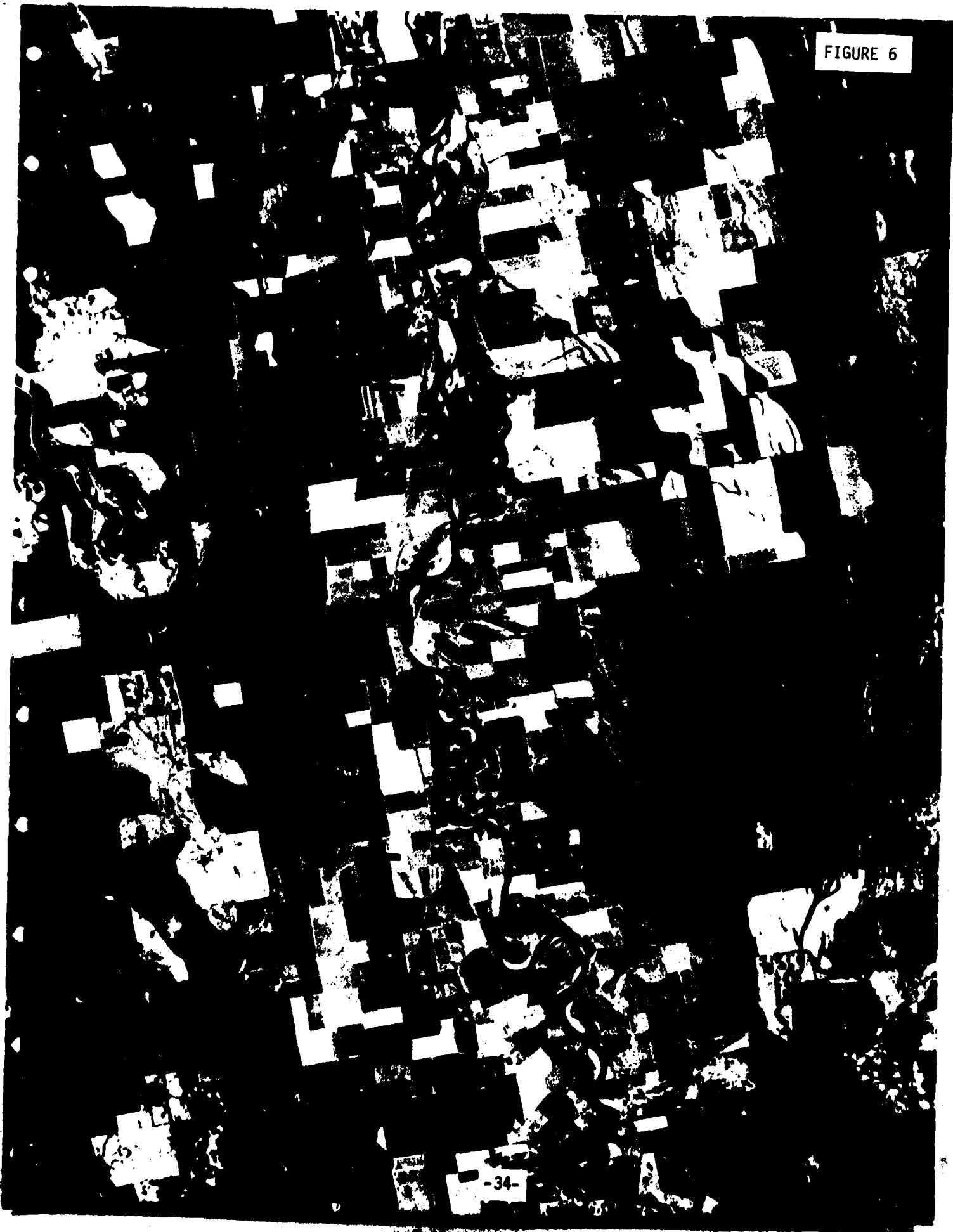
create increased noise in the final image. To reduce image noise, it is appropriate to employ low pass filter operators, i.e., smoothing algorithms. This leads to a "cleaner" image, but inevitably it degrades the apparent resolution of the resulting image.

Figure 6 illustrates the effect of a particular high pass filter (a 5-point Laplacian) on a good quality digital RBV image of California (compare with Figure 7).

It must be noted that both high and low pass filters (edge enhancement and smoothing operators) distort radiometric image properties, even when they increase the interpretability of the image. This is not too important in manual photo-interpretation, but becomes very significant if computerized analysis methods (such as image classification algorithms) are employed.

Images produced employing the radiometric and geometric corrections and enhancements described above constitute the GEOPIC processed version of Landsat images developed by Earth Satellite Corporation. Color examples of such images are shown in Figures 11, 12 and 13 of Section IV. Additional details of GEOPIC production and interactive processing of Landsat images are given in Section IV and also in Appendix 1.

FIGURE 6



IV. PROJECT EXPERIMENTS

In this section, general comments on the evaluation of different data types are provided, with a view to overall assessment of the quality and particularly the variability of relevant space-derived data.

Experience shows that image quality, even when obtained under apparently identical conditions (height, sun angle, viewing angle, and weather), is frequently highly variable.

The evaluation of test site images specific to this study, rather than of general data sources, is given in the interpretation results of Section VI.

A. Evaluation of Landsat Digital RBV Data

The first generally available digital RBV tape of Oroville, California, promised very high quality from this data source.

The original impression was that, suitably combined in the computer with MSS data, digital RBV data would permit the construction of false color images with an apparent ground resolution approaching 30 meters. A computer processed example of the Oroville scene is given in Figure 7, and a MSS-RBV computer combination for the Washington, D.C. area forms Figure 8. Neither of these examples contains the main classes of land use of prime interest in this study; therefore, tapes of coastal areas in Mississippi and Louisiana were obtained.

The results of processing those examples with suitable contrast adjustment and intensity stretches are shown in Figures 9 and 10. The degree of detail visible in these examples does not approach that seen in the Oroville, California and Washington, D.C.



FIGURE 8



FIGURE 10



scenes. It is difficult to accept that the resolution of these images is truly 35 meters, and in addition there were variations in overall image intensity across the scene.

Following the evaluation of these test site examples, and taking into account the difficulty and delays experienced in obtaining even these test tapes, it was decided that continued attempts to use digital RBV images as measures relevant to the potential of Landsat-D Thematic Mapper data would not be fruitful. Attention was therefore turned to the possible use of SEASAT SAR data as a high resolution alternative to digital RBV data. The interpretation described in Section VI uses Landsat and SEASAT data only, supplemented for verification purposes by aerial photography.

B. Evaluation of Landsat MSS Data

Landsat MSS images are usually at their most striking in areas of variegated land use, high relief, and exposed geology. Impressive examples of MSS images in these three categories are given in Figures 11, 12 and 13.

Generally speaking, images of coastal areas are flat, sedimented, and often uniformly vegetated. One therefore expects that Landsat MSS images for coastal application may appear less immediately useful. However, the presence of the 0.5 - 0.6 micro-meter band offers an advantage that neither the RBV nor SEASAT radar possesses; namely, a fair ability to penetrate shallow water, or, in turbid areas, the power to trace sediment plumes. Figure 14 shows

FIGURE 11

When you purchase EarthSat Landsat Photomaps, here's what EarthSat does:

- EarthSat selects the images to be used. Careful selection by professionals insures a minimum of cloud cover, reduces seasonal or annual image differences, and provides best available imagery coverage.
- EarthSat digitally processes and enhances the Landsat scenes, using the most advanced GEOPIC processing technology, to produce the best quality images for photomapping.
- EarthSat's experienced technicians process, color-balance, and mosaic the GEOPIC images, using existing maps or control for best-fit scaling and positioning.
- EarthSat works with you to design photomap legends, titles, and/or credit information appropriate to your needs.
- EarthSat formats the mosaics into a photomap series for your area of interest, and produces and delivers the desired quantity of photomap products.

EarthSat Landsat Photomaps can be produced in a variety of formats, scales, and materials to best suit your particular use or applications. Typical characteristics and applications include the following:

LANDSAT PHOTOMAP CHARACTERISTICS

Superior Quality Color Landsat Images
Same Format as Topographic or Other Maps
Semi-controlled (fitted to established cartographic controls)
Geographical/Spatial Perspective
Reproducible, Color or Black & White
Multipurpose Flexibility and Economy
Utilizes Existing and Current Data
Compatible with Other Planning and Cartographic Data

LANDSAT PHOTOMAP APPLICATIONS

Cartography — Landsat Images
Become Landsat Basemaps
Natural Resources Analyses — Vegetation, Forestry, Agriculture, Geology, Water Resources, etc.
Land Use and Land Capability Analyses
Land and Energy Exploration Development
Transportation Facilities and Network Planning
Communication and Reference Base
Education

LANDSAT MOSAICS

Mosaics provide a broad geographical overview of the physical resources and diverse environments of a nation or region. Prior to the launching of Landsat satellites, mosaics compiled from costly aircraft surveys were hampered by the lack of uniform lighting conditions which reduced detail and contrast of scene features.

Large area features and interrelationships of a nation's physical and cultural environments may be readily seen on Landsat Mosaics. They provide a vital communications tool for regional mapping, geographical studies, planning and multiple resource applications. They offer, for the first time, an opportunity to see the nation or region as it would be seen by astronauts, and in one view observe the relationships between the physical environment and the natural and cultural resources.

TECHNOLOGY TRANSFER

EarthSat is committed to developing advanced and cost-effective means for analyzing and understanding our Earth's resources, and to assist decision-makers in their programs to develop and manage our environment. Landsat Photomaps, Mosaics, and GEOPIC images are valuable tools, providing a superior data base for mapping, analysis, planning, and display.

EarthSat's Technology Transfer programs take many forms — each designed to meet specific needs and requirements, and to assess and improve local capabilities and expertise. These programs focus particularly on Developing Nations, by assisting local scientists, planners, engineers, and managers to make best use of Landsat and other remote sensing data, cartographic tools, analysis techniques, field surveys, etc., to understand, develop, and manage their nation's resources.

For more information concerning EarthSat Landsat Photomaps, prices, delivery schedules, technology transfer programs tailored to your needs and specifications, and other EarthSat services, call or write:

EARTH SATELLITE CORPORATION

FIGURE 12



FIGURE 13



GEOPIC PROCESSING

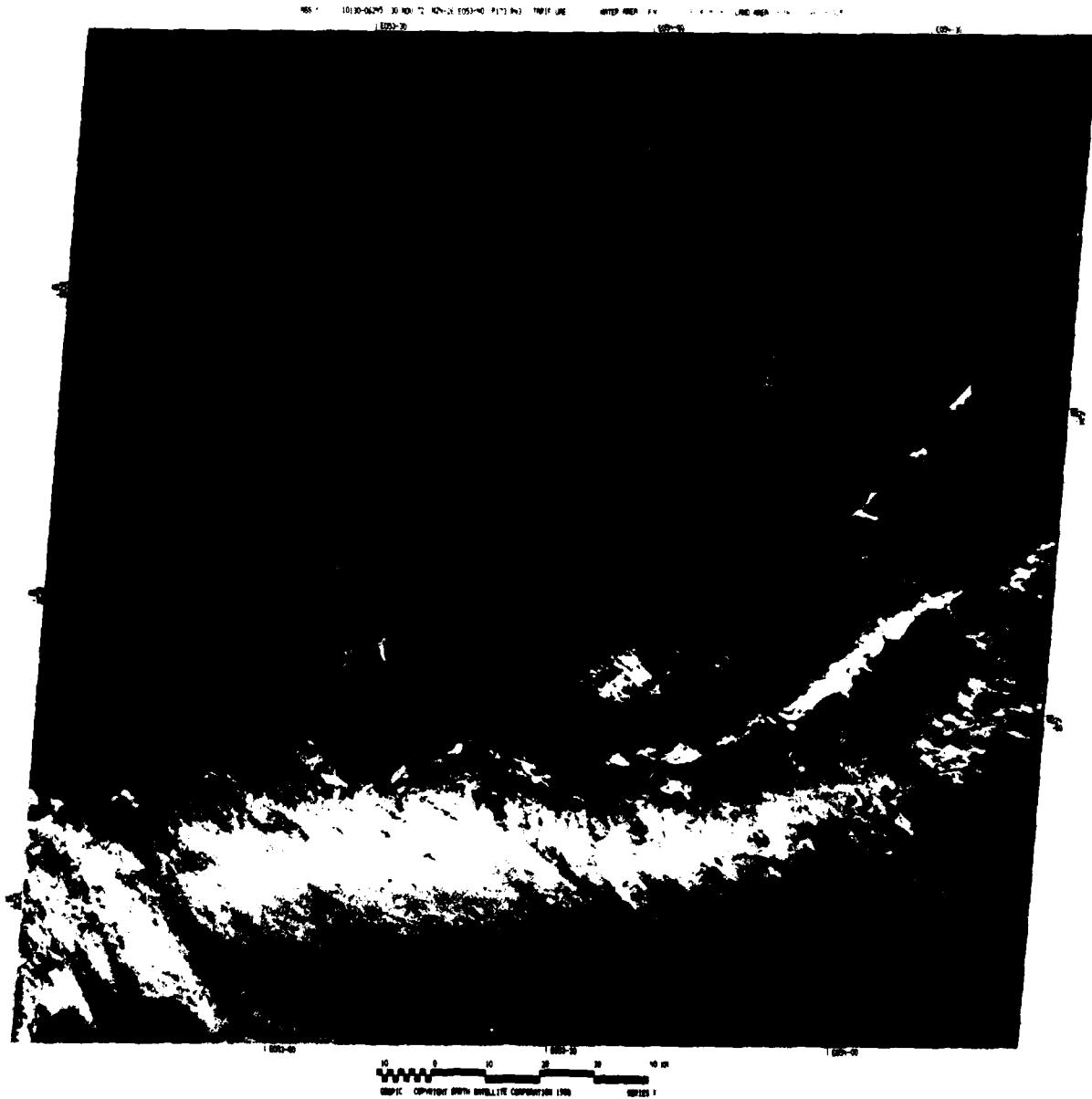
All GEOPIC images receive corrections for geometric and radiometric distortions in the raw digital Landsat data, unless otherwise specified, including —

- **Digital Edge Enhancement** Edge enhancement increases contrast of color and density along boundaries within an image. This process improves the analyst's ability to rapidly identify linear and border features such as agricultural field boundaries, land use interfaces, geologic faults, marked relief or structural changes, water body limits, soil type boundaries, lithologic changes, etc.
- **Gray Scale Adjustments** EarthSat's contrast enhancement algorithm stretches the range of reflectance values to maximize image information content. Gray scale adjustments can also be manipulated to visually highlight image areas of special interest.
- **Scan Line Removal** This unique algorithm suppresses regularly spaced scan lines (or "striping") in an image caused by repetitive malfunction of the satellite's multispectral scanner detectors. The process enhances image quality, eliminates processing of erroneous data, and greatly improves image interpretability.
- **Geometric Corrections** A series of algorithm improvements now result in maximum geometric accuracies in GEOPIC images. Systematic correction parameters include: satellite pitch, roll, yaw, heading, and altitude variations; image skew caused by both earth rotation (by latitude) and finite scan time; spectral band offsets; mirror scan velocity; and panoramic corrections for earth curvature. Scale accuracy is maximized in all directions for easy superimposition of overlay maps and charts.
- **Geographic Tick-Marks** 30-minute latitude and longitude tick marks provide GEOPIC image users with approximate coordinates for convenient cartographic reference data. These tick marks are located using the ephemeral data supplied by NASA on the CCT's of each image.



GEOPIC images, produced from a digitally processed Landsat image (1088-17384) acquired on September 19, 1972, show the San Rafael Swell in eastern Utah at approximately 1:1,140,000 scale. At left is a standard False Color Infrared GEOPIC image; on the right is a GEOPIC Eigen image of the same scene.

FIGURE 14



an example in which special digital processing has permitted the mapping of submarine topography to depths of more than 30 feet using only the Landsat MSS data as source, in an area where the water is clear. Although no data source is available to support the statement, it seems highly probable that the Thematic Mapper will be equally useful in the functions of sediment and bottom mapping. Pure, clear water is most penetrated by light with 0.48 micrometers wavelength. Water which is more turbid, because of suspended particulates, permits maximum light penetration at longer wavelengths. Figure 15 shows the relationship between optimal penetration wavelength and the presence of suspended matter in the water. The MSS Band 4, from 0.5 - 0.6 micrometers, extends a little beyond the best wavelength for water penetration, even in turbid areas. The Thematic Mapper has a band from 0.45 - 0.52 micrometers that is perfectly situated for penetration of clear water, and hence for the mapping of submarine features. The distinction between return signals from submarine features in clear water and from scattered radiation in turbid water is not easy. In general, the two physical variables will be confused unless other information is available. This subject is discussed further in Section VI.

C. Evaluation of SEASAT SAR Data

Radar instruments, sensing in the microwave region, show a differentiated return (and hence image detail) through variations in dielectric constant and aspect angle. Sudden changes from dry

COLOR PENETRATION CHART

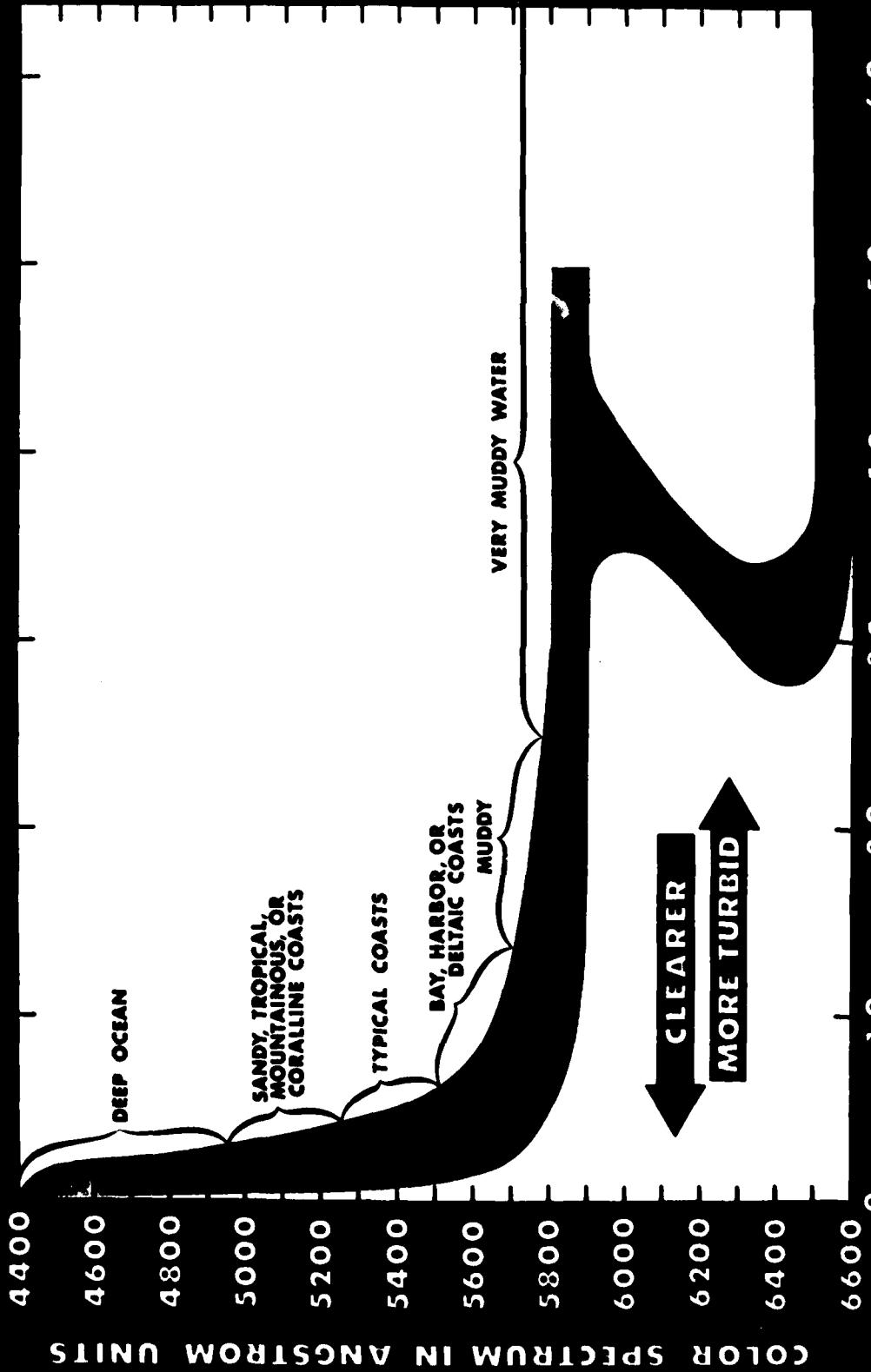


Figure 15

to wet surface, or sharp changes in terrain, maximize the amount that can be seen on a radar image. Microwave radiation has negligible ability to penetrate water, and therefore no submarine detail is observed.

Since coastal areas are frequently flat and low-lying, radar data may be expected to show land/water boundaries in great detail, but to provide no detail in the water, and to show land detail only due to changes in surface (such as from agriculture to urban, plowed soil to fallow soil, etc.). There is one exception to this statement. The SEASAT spacecraft was designed to permit the study of sea state. If there is a strong wind blowing at the time of image acquisition, radar images will show the direction of those winds through shadowing of water areas to the lee of the shore. Examples of this are shown in Section VI. An example of the value of SEASAT SAR images in an area with good surface geological exposure is given in Figure 16. Interpreter assessment of this image places the effective ground resolution in the 50 meter range. Data of this type and resolution will therefore add to the interpretations made from Landsat MSS data only if a phenomenon is distinguished by its microwave reflectance and not by its visible or near-IR reflectance.

FIGURE 16



V. SELECTION OF TEST AREAS

The selected test areas for interpretation in this study are centered on the towns of Elizabeth City, North Carolina and Duck, North Carolina, with the Elizabeth City test site as the primary area for analysis. The available data for the Elizabeth City test area is as follows:

- (1) Landsat MSS digital tapes
- (2) SEASAT full resolution SAR digital tape
- (3) 1:20,000 scale panchromatic black and white photography
- (4) 1:20,000 scale color infrared photography
- (5) 1:112,000 scale side-looking airborne radar
- (6) 1:9,300 scale thermal infrared film
- (7) 1:62,500 maps, from the 1940 to 1948 period
- (8) Ground truth photography and associated descriptive material (1980 survey)
- (9) Soil survey of Pasquotank County, North Carolina

The list of materials for the Duck, North Carolina area consists of:

- (1) Landsat MSS digital tapes
- (2) SEASAT full resolution SAR digital tape
- (3) 1:62,500 maps, from the 1940 to 1948 period
- (4) 1:12,000 scale panchromatic black and white photography
- (5) 1:2,000, 1:5,000, and 1:10,000 scale color infrared photography.

VI. INTERPRETATION RESULTS USING LANDSAT AND SEASAT DATA IN SELECTED TEST AREAS

A. Processing

Windows for the Elizabeth City and Duck test areas were identified on a 1:250,000 scale SEASAT image. Using a 1:1,140,000 Landsat GEOPIC print (Figure 17), appropriate row and column numbers for the Landsat CCT were calculated, and test area locations verified by display on a Grinnell interactive system (see Appendix 1 for Grinnell description). After inspection and contrast adjustment of the color images (Bands 4, 5 and 7) on the screen, 35 mm photographs were taken and developed to an approximate 1:250,000 scale. Initial interpretation utilized these photographs (Figure 18).

For the same selected windows, GEOPIC products were developed at a scale of 1:100,000, and a GEOPIC image of the whole scene using Bands 4, 5 and 7 was processed at 1:250,000. After image processing, comparison of the 1:100,000 scale windows with the 1:250,000 scene showed that greater feature size was gained at the expense of clarity in the large scale image. All subsequent interpretation was therefore performed using the 1:250,000 scale image (Figure 19).

B. Interpretation

A complete initial interpretation of the test areas was performed using the Landsat data alone. Following this, interpretation was made of the SEASAT SAR image test areas (Figure 20) to determine what additional information could be added to the Landsat data base. It would be misleading to conclude that features more visible on the SEASAT SAR image reflect the result of increased spatial resolution.

FIGURE 17

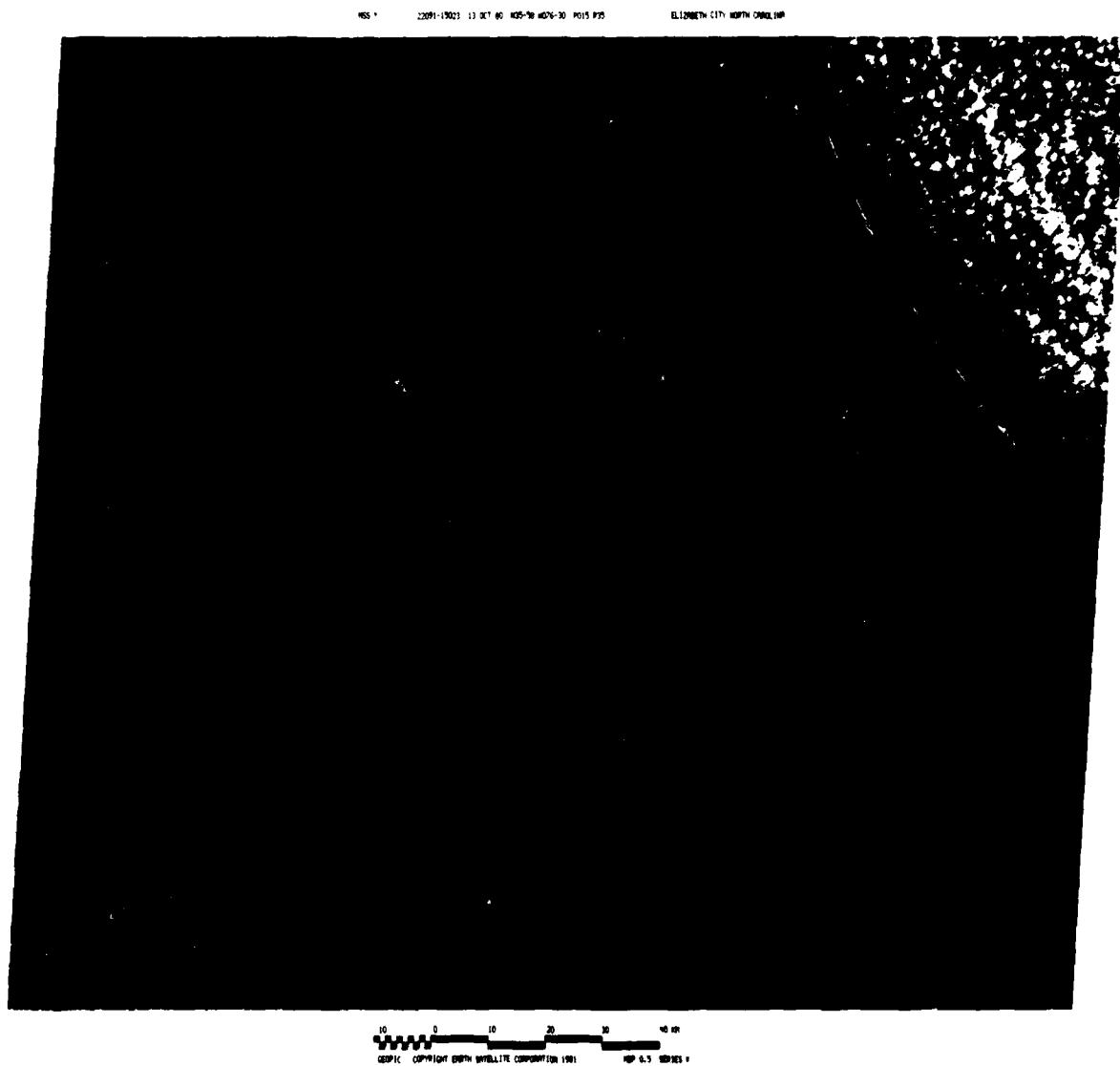
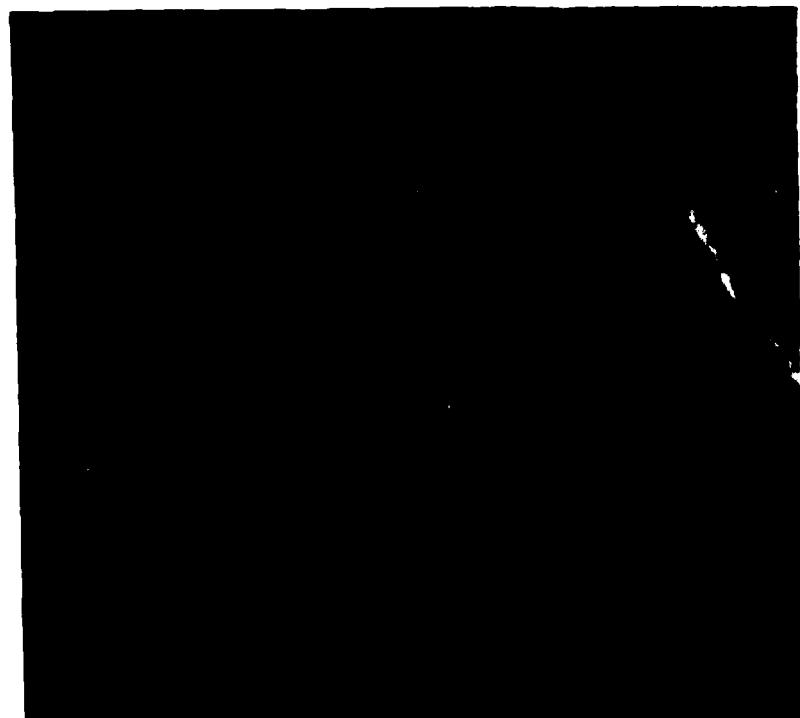
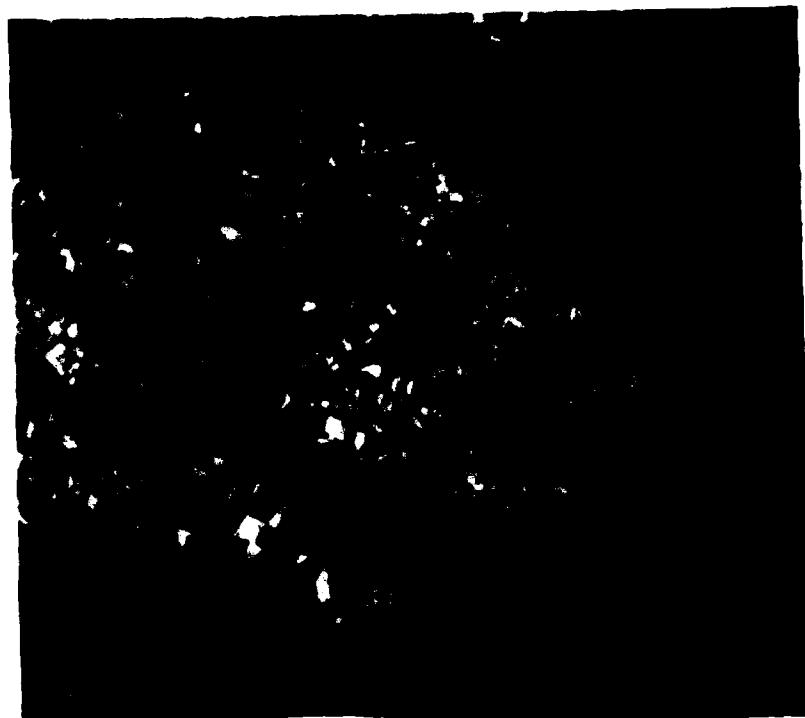


FIGURE 18



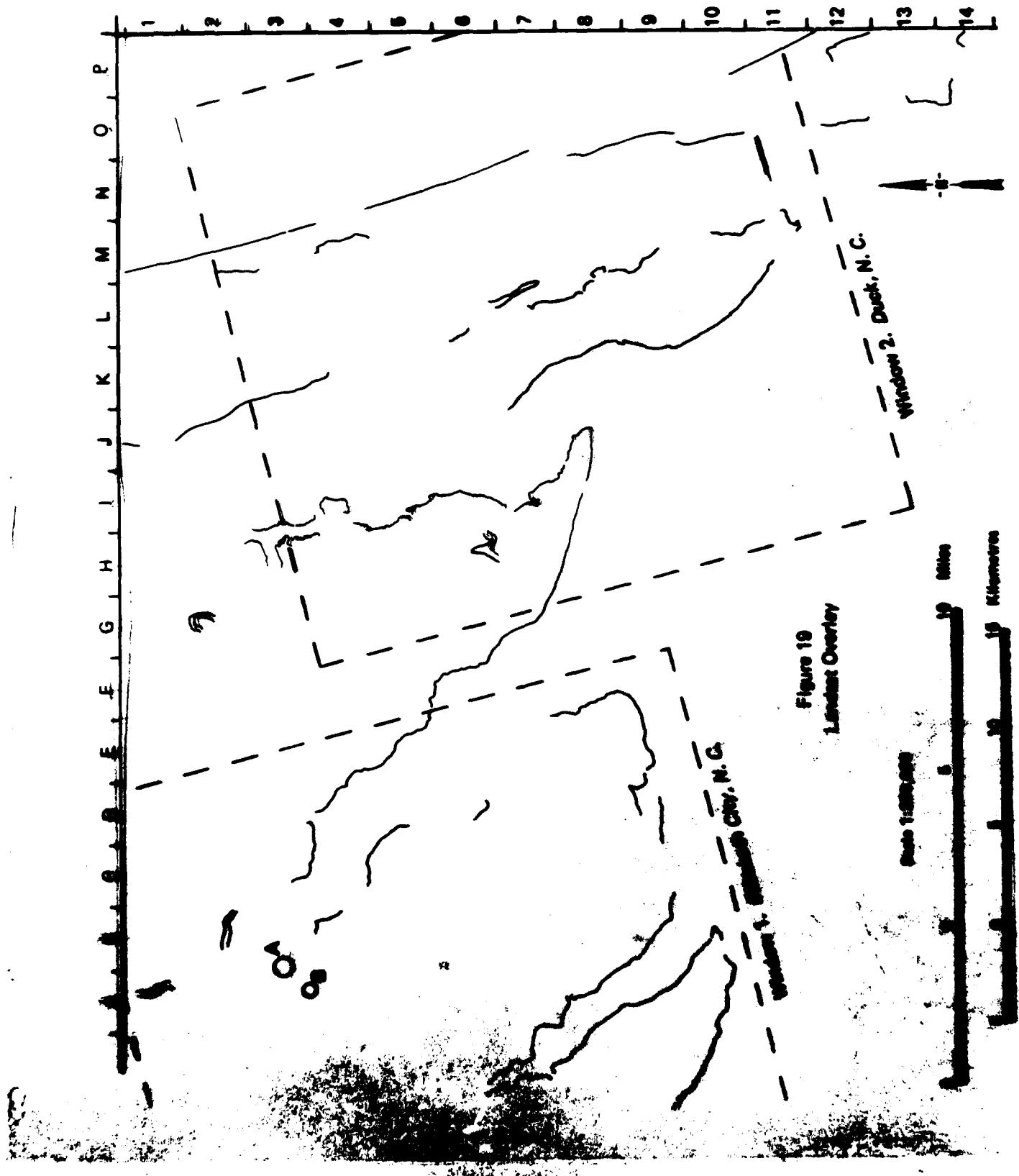


FIGURE 19

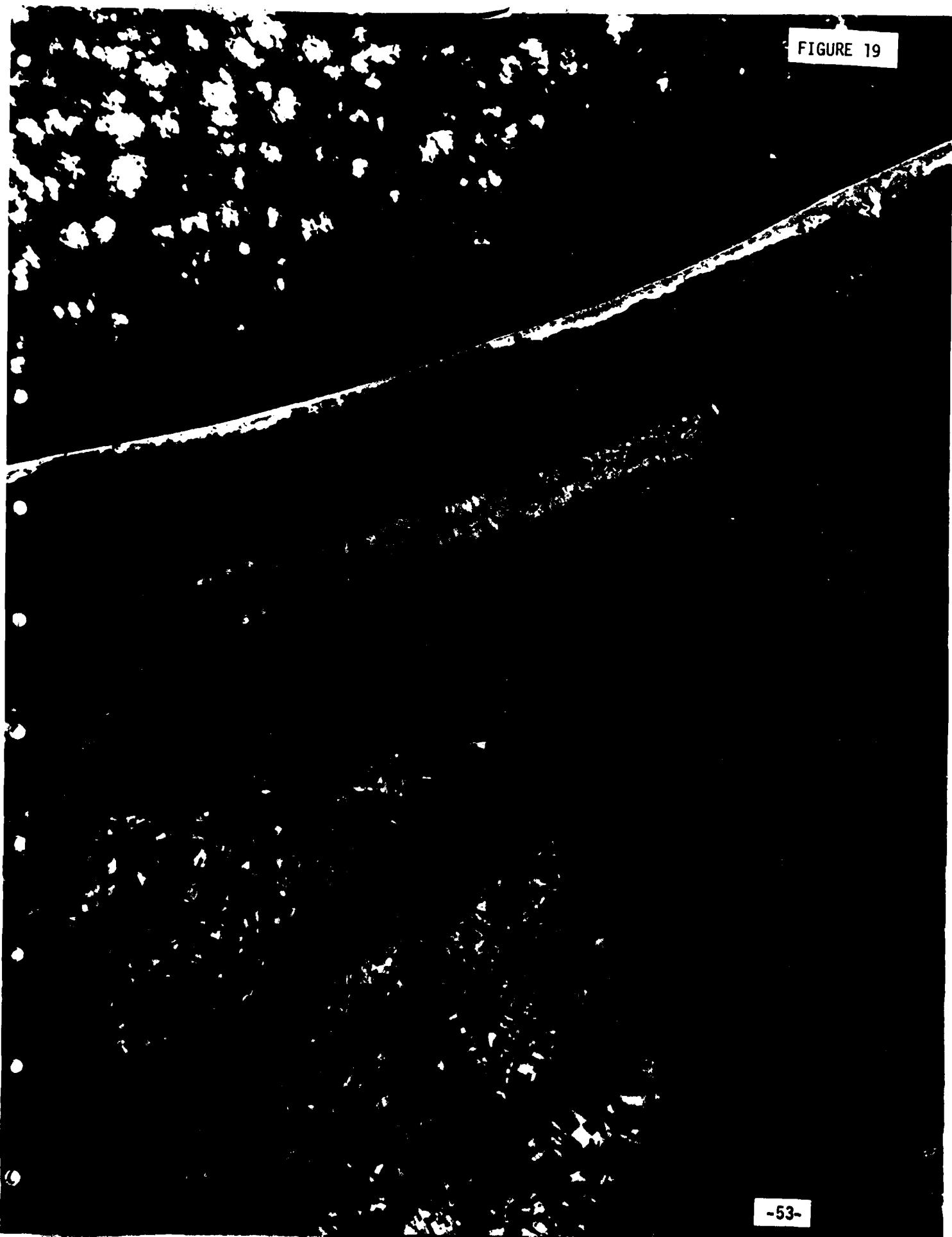
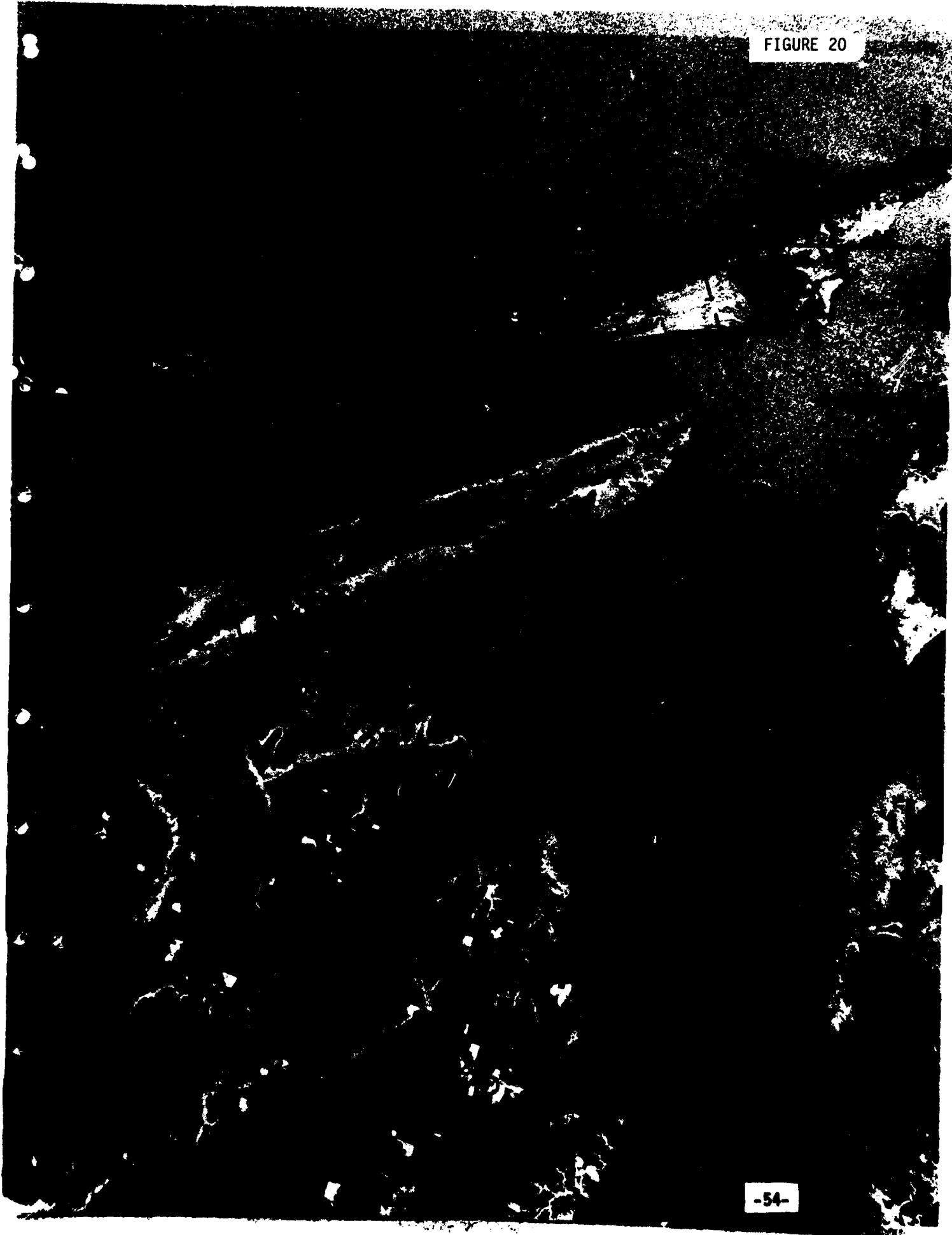


FIGURE 20



The examples on the SEASAT image where contrast is sufficient to permit improved resolution over Landsat are few in number.

Generally for these test sites, the high spectral resolution provided by Landsat allows visibility of land use classes and features which are less distinct or undetectable with SEASAT.

However, the addition of SEASAT SAR data provides valuable information based on surface texture, aspect angle, and change in dielectric constant. When these characteristics are more prevalent than spectral differences, features will be more easily detected on the SEASAT image.

The data sources complement each other and provide more information together than either does separately.

Results of the image interpretations follow, discussed by feature category. Overlays to Figures 19 and 20 for the Landsat and SEASAT images are referenced in the text to illustrate specific features. A summary of the most pertinent results is found in Table 3. SEASAT SAR interpretation was performed using an image without final range correction; however, the small size of the test areas compared with the total image size permits comparison of Landsat and SEASAT with little effect of distortion.

WATER PENETRATION & SEDIMENT FLOW

Maximum light transmittance in clear ocean water occurs in the spectral range between .44 - .54 μ m. In more turbid waters or those containing dissolved organic matter, the range of maximum

Table 3
INTERPRETATION OF TEST AREA IMAGES

Level of Feature Identification 1:250,000 Scale	Landsat MSS	SEASAT SAR
<p>I.</p> <p>Feature is distinctly visible and readily identified; configuration nearly certain.</p>	<p>A.1. Shoreline configuration: tidal inlets, inland waterway.</p> <p>B.1. First order land cover classification and borders, such as wetlands, forest, agricultural fields, sand dunes.</p> <p>2. River and stream drainage to primary tributaries.</p> <p>3. Agricultural field differentiation.</p> <p>C.1. Clearings through forest areas for roads/railroad tracks (indistinguishable).</p> <p>2. Bridges over large water bodies.</p>	<p>A.1. Delineation of land/water interface, especially in areas of mud flats and small islands.</p> <p>B.1. Rivers near the mouth and primary tributaries.</p> <p>2. River valleys, stream drainage patterns to tertiary tributaries- illustrated by extent of riparian vegetation.</p>
<p>II.</p> <p>Feature is clearly visible and can be identified; fairly certain of configuration or characteristics.</p>	<p>A.1. Water current-derived landforms, e.g., points, ridges and swales from barrier beach tides.</p> <p>2. Configuration of mudflats and islands, and vegetation variations within.</p> <p>B.1. Vegetation at or just below water surface (indistinguishable).</p> <p>2. Currents in shallow, sediment-laden water.</p> <p>3. Sediment outflow from rivers and agricultural areas.</p> <p>C.1. Isolated urban features surrounded by contrasting land cover, e.g., airport.</p> <p>2. Agricultural fields to a minimum of approximately 11,000 sq. meters.</p>	<p>A.1. Vegetation on or just below water surface (indistinguishable).</p> <p>2. Sand dune form, ridges and swales.</p> <p>3. Agricultural fields to approximately 9,000 sq. meters.</p>

Level of Feature Identification 1:250,000 Scale	Landsat MSS	SEASAT SAR
III. Feature is identifiable; characteristics blurred or indistinct.	<ul style="list-style-type: none"> A.1. Mudflat/water interface. 2. Zone of swash and/or shallow shore slope (indistinguishable). B.1. Secondary and tertiary stream drainage (forested areas). 2. Density of settlement patterns on urban areas and barrier islands: road grids, building clusters, aggregated land structures associated with port or harbor. C. Small bridges over rivers and intracoastal waterway. 	<ul style="list-style-type: none"> A.1. Densely built up urban areas and transition to other land uses. 2. Rough textured and/or recently irrigated fields. 3. Agricultural field differentiation.
IV. Feature is detectable; interpretive inference required for identification.	<ul style="list-style-type: none"> A.1. Sources for water spectral differences: sand, sediment, subsurface vegetation. B.1. Canals and irrigation ditches through forested and farmed areas. 2. Roads through agricultural areas. 	<ul style="list-style-type: none"> A.1. Pier and harbor structures abutting into water. <p>ITEMS IN IV AND V BELOW ARE LESS VISIBLE ON SEASAT:</p> <ul style="list-style-type: none"> B.1. Large scale (<23.5 cm) water patterns. 2. Single urban features: bridges, roads.
V. Not detectable.	<ul style="list-style-type: none"> A.1. Secondary and tertiary stream drainage through agricultural regions. 	<ul style="list-style-type: none"> A.1. Water depth or sediment, small currents. B.1. Airports or other flat areal features. 2. Canals, irrigation channels.
VI. Not detectable on either image.	<ul style="list-style-type: none"> A.1. Individual urban features where they are clustered. 2. Railroad bridges over water. B.1. Streams through urban areas. 2. Small islands (100 m or less). 	

transmittance shifts to longer wavelengths. Maximum penetration of marine water in a marsh environment occurs in the wavelength span of .55 - .63 μm , which closely corresponds to MSS Band 4 of Landsat.

Reflectance of scattered radiation in water bodies reveals sediment patterns and/or near-shore ocean bottom. This is illustrated in Figure 19 from M1 to O11. In order to determine which feature is being viewed a time series of images is required, since the signature cannot be positively identified on one image. Repeated coverage of the area will show whether shifting beach sediments or more stationary shore slopes are being revealed. Shallow water currents and sediment contribution from adjacent agricultural fields may also be monitored in this way. An example of the latter is seen at F7 on Figure 19.

Sediment from various sources can be differentiated on Landsat images based on spectral signature and inference from location. Turbidity near sandy beaches, once positively identified, will exhibit a very strong reflectance and a light tone on the image (O8 on Figure 19). This changes to a darker pattern near river mouths and marshes where sediment tends to contain more mud (K3 on Figure 19).

Sediment flow helps to illustrate water currents. For this reason, on Landsat images, current patterns are much less visible in deeper water. Circulation in deep water areas surrounded by more shallow water can be inferred, however, by the adjacent near-shore patterns (M13 and H14 on Figure 19).

On the SEASAT image, water agitation at a scale greater than the wavelength of the radar signal (23.5 cm) can be detected, providing an idea of the gross surface currents and texture.

Dark patches are visible in the more shallow water near shore (I1 and L1 on both images). After initial inspection of the Landsat image, it was thought that these might be areas of surface vegetation growth or deeper, less turbulent water with little sediment. Comparing the Landsat and SEASAT SAR data revealed that this was not the case. Since the radar signal does not penetrate water, corresponding areas of low reflectance on the SAR image imply that the phenomenon is surficial, and that the water surface in the dark patches must be smooth. It was concluded that the patterns result from mud flats or aquatic vegetation just below the water surface. The vegetation is manifested on the Landsat image as a darker signature and on the SEASAT image as an area of smooth water (low reflectance) resulting from increased friction near the surface. This is an excellent example of the complementarity of MSS and SAR data and the insights that can be gained by their combined use.

SHORELINE & INLET FEATURES

Both Landsat and SEASAT images exhibit high resolution of shoreline and inlet features (I4 on both images). Although wind shadow may cloud some shoreline subtleties, SAR supplies additional feature visibility in marsh or island areas. Subtle shoreline characteristics are visible where low marsh/water spectral differences

may have muted them on Landsat imagery (M6 on Figure 20).

Isolated islands 100 meters or less in diameter, readily discerned on panchromatic aerial photography, are not visible on either the Landsat or SEASAT image.

SAR ability to detect even slight topographic differences is also seen in the improved detection of sand dune configuration (09 on Figure 20). Landsat provides detail of vegetation variation on the dunes and within marsh areas.

STREAM DELINEATION

Stream and river delineation is also enhanced by the concurrent use of MSS and radar data. As seen in C6 and C9 of Figure 19, inlets, rivers, and their primary tributaries are distinctly visible on Landsat imagery. However, smaller tributaries of inland drainage, especially those occurring in agricultural areas, become difficult or impossible to detect due to low spectral variation between agricultural fields and the narrow strip of riparian vegetation.

In addition to river delineation, SAR imagery clearly illustrates river valleys and stream drainage patterns to the level of secondary and tertiary tributaries (B4 to C7 on Figure 20). This high return results from surficial dielectric properties associated with high moisture levels in riparian vegetation, and also its relative surface roughness. The same response is visible from scattered agricultural fields such as in C2 in Figure 20. This additional data is especially useful

for drainage patterns through agricultural or densely forested regions, where MSS information is often muted or lost. Stream drainage through urban areas is not visible with either medium.

URBAN AREAS & FEATURES

Individual features in urban areas are not readily identified on either the MSS or SAR imagery, unless they are isolated amid a background of high contrast, spatially or texturally.

The airport at C5 on Figure 19 is quite obvious on the MSS image but is lost altogether on SEASAT due to its smooth texture. For the same reason, small linear features such as roads, small bridges, canals, and irrigation channels are not visible on SEASAT, despite the theoretical 25 meter resolution.

An exception to this occurs where linear features extend into water. Thus, Elizabeth City harbor features are detectable within circle A on SEASAT (Figure 20). The bright spot in the water above may be a ship or barge. The 610 meter Duck FRF pier can be seen at 07 on Figure 20 and a smaller fishing pier is visible within circle B.

These features are not visible with Landsat, which provides better detection of inland linear patterns. Canals and/or irrigation channels are intermittently visible (I8 on Figure 19) where they pass through forested areas. This is also true for roads (B3 on Figure 19) and railroad tracks (B2 on Figure 19) which are visible but indistinguishable where they cut a swath through forest lands. These features are lost where they traverse urban or agricultural land cover. The intracoastal waterway is clearly seen (I2 on Figure 19)

and small bridges over water may also be detected. The Pasquotank River bridge within circle A on Figure 19 is approximately 115 meters long.

General urban settlement patterns are seen on both images but again the information differs. The main auto routes through Elizabeth City are visible by inference on Landsat where spectral differences of paved and built surfaces cause the linear pattern to stand out from the surrounding land cover (A3 on Figure 19).

Similarly, general road grids are visible in the surrounding residential areas. Delineation of urban land use is unclear with Landsat where merging of land cover makes borders indistinct. SAR data is even less reliable for urban/non-urban separation, since outside the high reflectance area of inner city and docks, no urban/non-urban transitions can be observed on the image (A3 on Figure 20). Combining data from both images provides detailed information on urban settlement density patterns.

AGRICULTURAL PATTERNS

Transition between other land classifications is not as clearly seen on SAR as on MSS imagery. The boundaries between agricultural land and forest are indistinct, and identification of different field types is even more difficult. Although direct comparison of field conditions cannot be made between the images since they were taken during different seasons and years, the high spectral response of Landsat provides superior resolution

of field/forest patterns and agricultural field types. The fallow (blue) field located within circle B on Figure 19 is approximately 106 meters on each side and illustrates the minimum field size which can reasonably be delineated. Distinction between recently cleared fields (white) and those covered by crops in different growth stages (various shades of red) is readily made.

In this respect, contrast on the SEASAT image is much poorer and fields which can be confidently delineated are generally larger than on Landsat. The field in circle C of Figure 20 has approximate dimensions of 515 meters x 230 meters. In areas of high contrast, fields smaller than those visible on Landsat can be resolved, as in circle D on Figure 20 where each side of the field is approximately 95 meters.

Examples on SEASAT imagery where contrast allows resolution to this level are very few, and generally visibility on this SAR image is reduced as compared with the spectral contrast of Landsat. However, the images used in tandem provide much more information than either does separately. Features best delineated on MSS imagery are those which possess considerable spectral variation such as land/water interfaces and areas of differing vegetation. Landsat resolution is good for shorelines, land cover variations of forest, wetlands, and agriculture, and, to a lesser extent, urban areas. SEASAT augments Landsat data in areas of marsh/water interface,

stream drainage through varying land cover, urban development patterns, and coastal abutments. Additionally, new information can be gained about many features by adding SAR data, with its indicators of angle, surface texture, and moisture content, to the spectral characteristics provided by Landsat. Thus, although the spatial resolution of this SEASAT image does not approach the theoretical 25 meters, its unique characteristics add useful information to a Landsat data base.

VII. CONCLUSIONS

The principal conclusions to be drawn from the work of this project are as follows:

- (1) Both Landsat MSS and SEASAT SAR data are useful in providing a broad overview of coastal configurations, borders and land cover classifications. Neither data source is capable of providing the level of detail available from either panchromatic or color aerial photography, and cannot be regarded as a substitute for the latter.
- (2) If one were forced to choose one data source, either Landsat MSS or SEASAT SAR, to apply to civil works programs, that choice would be Landsat MSS. In principle, the superior spatial resolution of the SEASAT data should compensate for the superior spectral nature of the Landsat MSS data. In practice, the SEASAT SAR data does not look any better in spatial resolution than the Landsat MSS data. Rather than being 25 meters, as the specifications for full resolution SEASAT SAR data suggests, the images analyzed on this project appear to be of a resolution no better than 75 to 100 meters.
- (3) Despite the point made in (2) above, there are significant advantages to employing MSS and SAR data in concert. As Table 3 of Section VI clearly revealed, a number of features, particularly those relating to land/water interfaces, are more readily visible on SEASAT SAR data. The two data sources together are stronger and more reliable than either taken separately.

- (4) The results obtained from this study leave uncertain the value of increased spatial resolution data in the Landsat wavelength range. The physical variables measured by the SEASAT SAR and Landsat MSS imaging systems are radically different. The only realistic way to evaluate the Thematic Mapper data is through the use of a data source which senses in the same or similar wavelength regions.
- (5) Enhancement processes both for Landsat and SEASAT data have a huge effect on the interpretability and therefore the value of remotely sensed information. It is likely that the pre-processing which had already been applied to the SEASAT data had lost enough information to make a true test of the potential of that data source impossible. The degree of detail visible on the collateral airborne radar images used for confirmation results on this project re-emphasize the power of high resolution radar data as an interpretive tool, even in areas without significant terrain relief. A higher resolution spaceborne radar instrument should be a tool of great value in coastal mapping.

VIII. RECOMMENDATIONS FOR FUTURE SIMULATIONS

The best practical way to evaluate the potential of Thematic Mapper data from Landsat-D is via the calculated degradation and subsequent analysis of high resolution airborne scanner data with the same spectral bands as the Thematic Mapper. A number of overflights of the U.S. in non-coastal areas have been made by aircraft carrying a multispectral scanner with frequency ranges equal to those of the Thematic Mapper. Following pre-processing to remove wide angle effects associated with the much lower altitude of the aircraft compared with the spacecraft, the data can be degraded to match the 30 meters expected of the Thematic Mapper. Analysis of this data source avoids the main problems (of image registration, and of compatibility of spectral bands) that caused difficulties in performance of this project.

We recommend that a flight of an airborne Thematic Mapper Simulation Scanner be considered over the same test areas as Elizabeth City and Duck, North Carolina. The completeness of the data base, as itemized in Section V of this report, suggest that all the tools are at hand for a very thorough and informative analysis of the simulated Landsat-D data.

Although the launch of Landsat-D is now only one year away, the suggested simulations are still worth performing, since the Landsat-D data stream for the Thematic Mapper is not projected to become operational at reasonable scene volume until 1984 or 1985.

The Thematic Mapper also contains spectral channels (1.55 - 1.75 micrometers and 2.08 - 2.35 micrometers) that should be of great value in mapping of clays and silts. It is recommended that experiments be undertaken to concentrate on the possible value of these two channels.

Nothing in the present experiments using Landsat MSS or SEASAT SAR gives any indication as to the information content of these longer wavelength infrared channels. The same degraded resolution airborne scanner data would allow an assessment of the value in civil works of these new spectral bands.

The existing ground truth for the North Carolina test sites is detailed enough to allow an excellent evaluation of new data sources, whether through simulation of Landsat-D data or otherwise. It is recommended that the value of this collateral data base be emphasized, and suitable use be made of it in subsequent experiments evaluating remotely sensed data.

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APPENDIX 1

Reference was made in the main text to the GEOPIC image products, and to the Grinnell interactive system. These are described in summary here. GEOPIC takes Landsat MSS data, computer processes it to perform radiometric and geometric corrections, performs contrast adjustment and edge enhancements under direction from the Grinnell, and photoprocesses the resulting enhanced images. The system of programs to perform these manipulations of the data runs on a Prime 456 minicomputer, with 512K of main memory, 332 megabytes of disk storage, two 75 IPS tape drives, and a Grinnell 270 interactive display device.

The Grinnell 270 permits the storage and display on a TV screen of four 512 x 512 image windows, with an ability to extract and statistically analyze any subarea of the window using a joystick and movable cursor to control area selection.

The general processing consists of the following stages:

- (1) Employing as input Landsat MSS computer compatible tapes, pre-processing of the full image is performed for radiometric and geometric corrections.
- (2) Extraction of image statistics is performed, either for a full scene or for a selected area (for example, by using the Grinnell, it is possible to identify particular land or water areas for which statistics are to be developed).
- (3) From the computed image statistics, optimized contrast adjustments are generated, and the full image is then enhanced by application of these adjustments.
- (4) The resulting images are checked, in whole or in part, by re-display on the Grinnell screen.

- (5) If required, stages (2) through (4) are repeated until a satisfactory image results. An output tape is then created.
- (6) The output magnetic tape from the Prime/Grinnell system is read by an Optronics P1500 tape-to-film writer, which converts pixel grey levels to grey tones on a black and white film. For each spectral band, the Optronics is used to generate a black and white 9" x 9" positive transparency.
- (7) Three black and white positives (for Landsat MSS, Bands 4, 5 and 7 are used for a standard false color GEOPIC product) are registered, a contact scale color negative is developed, and final prints at any required scale are produced using photographic enlargement.

In addition to the standard products, the GEOPIC system also permits the production of digital ratio images, digital scene enlargement, principal component images, and scene multispectral classification. The general procedure to produce each of these products is identical to that described in steps (1) through (7) above, and each begins from the same input Landsat MSS computer compatible tape.

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